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ONR BAA 06-007 Phase 1 Final Technical Report

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Mercury Data Systems

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Abstract

This Final Technical Report provides details on the technical accomplishments of the ***ONR BAA 06-007 - Navigation in a GPS Denied Environment*** *phase I project activities. The contents of this document were derived from analysis of the state of art technical literature, available commercial off the shelf products and design efforts of MDS engineering resources. This content will be utilized to design and construct the prototype systems that will be delivered as part of the Phase II effort.*

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Confidentiality Statement

The information contained herein is approved for Public Release; distribution is considered Unlimited/Unclassified.

Preface

Mercury Data Systems (MDS) was awarded and began work on the ONR BAA 06-007 Navigation in a GPS Denied Environment Program contract on August 1, 2006. During this ONR BAA 06-007 Phase I activity, different approaches for integration of wearable absolute and relative position sensors have been investigated. Using prior knowledge of GPS denied navigation and mapping system requirements, MDS and ITT Teams performed research and development activities in support of the thirteen (13) technical capabilities defined in the contract statement of work. This Final Technical Report documents the results of the effort for the design and describes the relevant technologies required to achieve the desired system capabilities. It also describes our recommendations for future work in Phase II towards the completion of the detailed design and the construction of the prototype/objective system.

We have established four methods for localization: 1) Pseudorange localization via auxiliary data sources, 2) Range based localization via TOA (Time of Arrival), 3) Range free localization via INS (Ineritial Navigation System), and 4) Manual localization via Maps and Landmarks (LMs). In our approach, auxiliary data sources and Maps/Landmarks, when and where available, will provide absolution position information while TOA and INS will complement each other to help maintain this absolute position information as well provide relative position information. We have also devised innovative TOA techniques to reduce localization error in multipath condition as well as innovative INS mechanization techniques to reduce positioning error over distance/time traveled. In addition, we have devised an innovative communication/networking approach to distribute position information throughout the area of operation (AO) without exceeding the SEP error budget goal of the BAA. Similarly, our approach will meet other BAA goals including cost and form factor. In that regard, we have completed product analysis and identified major system components as well as activities and tasks required to prototype the system in Phase II

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1 Introduction

1.1 Scope of the Document

Mercury Data Systems (MDS) was awarded and began work on the ONR Navigation in a GPS Denied Environment (NAVGPSDE) Program contract on August 1, 2006. During this ONR BAA 06-007 Phase I activity, different approaches for integration of wearable absolute and relative position sensors have been investigated. Using prior knowledge of GPS denied navigation and mapping system requirements, MDS and ITT Teams performed research and development activities in support of the thirteen (13) technical capabilities defined in the BAA. This Final Technical Report documents the results of the effort for the design and describes the relevant technologies required to achieve the desired system capabilities. It also describes our recommendations for future work in Phase II towards the completion of the detailed design and the construction of the prototype/objective system.

The purpose of this Final Technical Report document is:

- To document the results of the effort for the design, and
- To describe the relevant technologies required to achieve the desired system capabilities, and
- To communicate the proposed system's capabilities and user expectations, from the development group to the ONR program management team and system end users; and
- To build consensus between MDS and its subcontractor (ITT), and among the MDS development resources; and

The audience for this report includes the following:

- The development team (MDS and ITT) will use the report as a basis for system development activities, and to familiarize new team members with the problem domain and the system to which this design applies; and
- The ONR program management team will use this content to help determine if the MDS proposal will be selected for continuation of the development efforts into Phase II of the project.

This document is divided into sections that describe the proposed solution and recommended future work for Phase II. This document is organized as follows:

Section	Topic
1	Research Objectives/Scope
2	Description of Relevant Technologies
3	Results of Required Studies
4	Technical Accomplishments
5	Proposed Future Work
6	Appendices

1.2 Research Objective(s)

The following technical objectives have been identified for this Program.

Objective 1: Research, design and develop a multi-sensor positioning system capable of self/remote localization by each clique member.

Objective 2: Research, design and develop fusion algorithms for the multi-sensor positioning system.

Objective 3: Research, design and develop algorithms to initialize and maintain a referential coordinate system for the clique.

Objective 4: Research, design and develop distributed, fault tolerant voting algorithms to synchronize individual position estimates throughout the clique.

Objective 5: Research, design and develop visualization capabilities for displaying the relative locations of clique members.

Objective 6: Research, design and develop user interface capabilities that enable simplicity and ease of use.

Objective 7: Research, design and develop communications processes to support:

- Auxiliary Data Sources
- Security
- Text Messaging
- Military Radio Interface

Objective 8: Create objective system specifications that meet program Size, Weight and Power goals.

Objective 9: Research, design and develop system configuration models that meet program Performance capabilities and Cost goals.

Each of these objectives is directly aligned with the desired capabilities of the BAA. At the same time, the sum of the objectives provides a complete solution that will meet all desired capabilities and goals of this Program.

The following tables provide references to guide the reader and it associates the desired capabilities and goals as stated in the ONR BAA to the Objectives listed above. The table also indicates the delivered capabilities as a result of this effort and the relevant technologies employed to deliver those capabilities.

Table 1: BAA Capabilities and Relevant Technologies.

#	Capabilities	Relevant Technologies	Delivered Phase II	Delivered Production	Objective (s)
1	The system should not burden the deployed forces in either volume or mass.	▪ MEMS–based INS, ▪ ASIC–based RF ranging and communications platform ▪ SBC within SWAP	Meet weight but not volume	Yes	3, 8, 9
2	The system should "just work" requiring minimal-to-no training for operation.	▪ Intuitive and simple to use lightweight user interface.	Yes	Yes	3, 6, 9
3	The system should be prepared to operate in a GPS-limited or GPS-denied environment.	▪ Multi-sensor approach ▪ Absolute positioning sources (GPS and Maps) ▪ Auxiliary data sources (Pseudolites and CMR beacons) Initialization of local maps (Referential Coordinate Systems)	Yes	Yes	1, 2, 3
4	The system should operate in open spaces as well as underground or cave-like settings.	▪ Auxiliary data sources, distributed ad-hoc ranging-based algorithm ▪ Complementary TOA/INS approach	Yes	Yes	3, 4
5	The system should provide for the fusion of multiple references in order to provide location information.	▪ PosiFusion algorithm based on Kalman filter.	Yes	Yes	1, 2, 3

#	Capabilities	Relevant Technologies	Delivered Phase II	Delivered Production	Objective (s)
6	The system should provide for auxiliary data sources/beacons for location information.	▪ Pseudolites ▪ CMR beacons ▪ Loran.	Yes	Yes	1, 2, 3
7	The system should provide for auxiliary data relays when in an underground or cave-like setting.	▪ System nodes used as relays in the production system.	Yes	Yes	3, 7
8	The system should provide for information security during data transfer consistent with the NSA Suite B (http://www.nsa.gov/ia/industry/crypto_suite_b.cfm).	▪ WSRT designed with an SCA compliant, flexible architecture	Yes – CMR is designed with SCA compliant flexible architecture ready for embedment in NSA suite B standard	Yes	7
9	The system should acknowledge when it is operating in a degraded information mode.	▪ An intuitive and simple to use lightweight user interface.	Yes	Yes	3, 5, 6
10	The system should provide for a limited/text-based data transfer from tracked/remote nodes.	▪ An intuitive and simple to use lightweight user interface ▪ Pre-canned messages for text-data entry.	Yes	Yes	7, 6
11	The system shall provide for operation of 100m into underground or cave-like environments (use of up to three relays is permissible).	▪ System nodes will be used as relays in the production system	Yes	Yes	3, 7, 9
12	The system must provide a standard military radio interface (mechanical, electrical, data).	▪ CMR radio ▪ Ethernet ports.	Yes option of CMR or standard radio	Yes	7
13	If relays are used as part of the system solution, said relays should be disposable and spoofing and tamper resistant.	▪ "Zeroize" feature on the UI ▪ CMR TRANSEC capabilities ▪ Tamper detection on SBC / Enclosure	Not required	Yes	3, 7, 9

2 Description of Relevant Technologies

2.1 Approach

2.1.1 Overview

As illustrated in the figure below, we have established four methods for localization:

1) Pseudorange localization via auxiliary data sources
2) Range based localization via TOA (Time of Arrival)
3) Range free localization via INS (Ineritial Navigation System)
4) Manual localization via Maps and Landmarks (LMs).

Figure 1 shows an overview of our approach. It focuses on the ability to exchange developed positions between members of the clique. Absolute position (AP) is determined through GPS at beginning of 8-hour duration. Absolute data may also be acquired via calibration with landmarks and maps at the boundaries of the area of operation since the clique members may be transported via air or by vehicle. Afterwards, absolute/relative position (AP/RP) information is distributed throughout the network both in time and space using different methods suited for different operational scenarios and terrains.

For outdoor scenarios, absolute position is distributed throughout the network via an innovative ranging-based distributed protocol (referred to as eLNS or **e**xtended Leapfrog Navigation System) to reduce/minimize relative error in urban canyons. eLNS is based on LNS (Leapfrog Navigation System) algorithm (Opshaug, 2002). eLNS takes advantage of node mobility to better select new set of reference anchors that can be used for accurate localization and positioning via iterative trilateration.

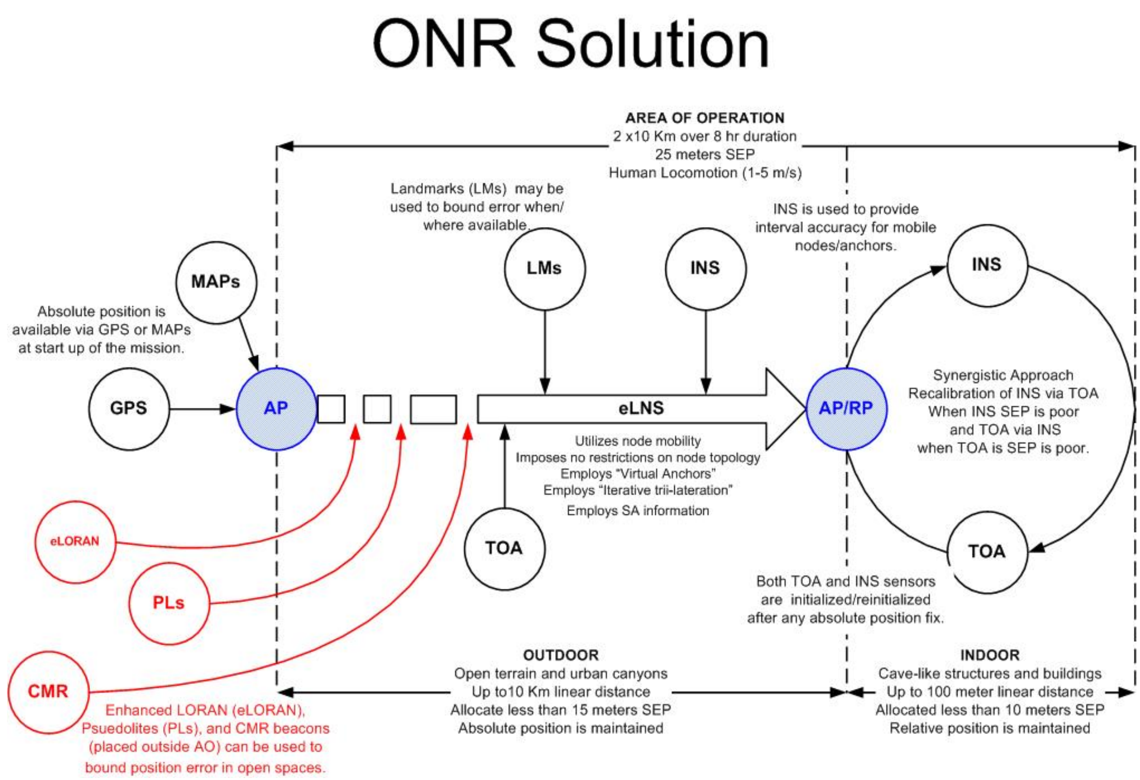

Figure 1 – System Overview.

The LNS algorithm works as follows. In LNS, all units are mobile, effectively increasing system range by more than an order of magnitude. The LNS algorithm requires known initial positions. After calibration, nodes are divided into two groups. One group starts out in their known stationary positions, while the others move into an area of interest. At some point, the mobile units stop, their positions are calculated using cross-range measurements, and the stationary group is released to move. In this way, the group as a whole can travel (leapfrog) towards a common goal. The LNS algorithm provides for solving positions of the mobile units using cross-range measurements from all stationary units in addition to the cross-ranges among the mobile units. Statistical covariance analysis for the pre-leap mobile positions indicated that position accuracies depended on the size of the fundamental range errors and relative geometry of the total system. The LNS approach also employs a recursive algorithm to estimate total position errors after N leaps of any distance. In addition, it uses a metric for estimating effects of multipath on positioning systems in cluttered environments. This metric is the Strongest Arrival Delay (SAD), a first order estimate of the ranging bias introduced by multipath that is stronger than a direct path signal. Indoor and outdoor navigation channel measurements were used to model ranging errors. Given ranging errors and system topology, the total range of LNS is estimated for a tolerance on absolute position errors. Using 100 m baselines and 200 m leap distances, nodes in LNS could travel almost 15 km before accumulating absolute position errors of 10 m (1σ) with as little as 8% stationary nodes at any given time. The LNS approach demonstrates that it is possible to navigate an area equal to the NAVGPSDE area without fixed infrastructure.

eLNS has the following features:

- Unlike LNS, eLNS exploits mobility to improve the accuracy and precision of localization and reduce the number of required anchors since node mobility may result in better GDOP,
- eLNS does not impose any restrictions on node topology.
- eLNS employs the concept of "Virtual Anchors" where a new set of anchors are selected for each epoch (defined by a leapfrog distance or leapfrog period) depending on node role, mobility, and network topology and geometry.
- eLNS employs "Iterative trilateration" where localized nodes may act as virtual anchors for un-localized nodes.
- eLNS employs SA information to adjust epoch size, and in turn, to bound error accumulation within SEP budget.
- Epoch size and Number of epochs are determined based on BAA requirements for human locomotion over 10 Km linear distance and 25 meters SEP (as described in the attached spreadsheet and is summarized in Section 2.3). We should also point out here that LNS has demonstrated 10m CEP in 15Km navigation and that we expect eLNS performance to be marginally worse than LNS performance due to uncertainty introduced by node mobility (but still within requirements).

eLNS incorporates features from other algorithms including Mobile-Assisted Localization (MAL) (Priyantha et al, 2005), Monte Carlo Localization (MCL) (Hu and Davis, 2004), Iterative Localization System (ILS) (Liu et al, 2006), and AdHoc Localization System (AHLoS) (Savidas, 2001). Specifically:

- Similar to MCL, eLNS exploits mobility to improve the accuracy and precision of localization and reduce the number of required anchors since node mobility may result in better GDOP,
- Similar to AHLos, eLNS employs an iterative trilateration/positioning technique to reduce computational complexity and communication overhead. eLNS starts from anchors and uses local computation to iteratively localize free nodes - positional information propagates from the anchors to their neighbors, and on into the rest of the network.
- Similar to MAL, eLNS employs Virtual Anchors and collaborative trilateration, similar to AHLoS, to mitigate the problem of low node connectivity (and a small number of well-separated anchors). Additional information is used to introduce temporary "virtual" nodes at strategic locations to calculate distances between regular nodes that are otherwise out of each other's range.

- Similar to ILS, eLNS employs an error-control mechanism to mitigate the problem of error propagation and accumulation.

eLNS works as follows. At start-up:

- All nodes learn their locations from GPS or manually configured.
- A set of virtual anchors are selected based on role, mobility, connectivity and geometry (information in the SVT).
- Anchor nodes propagate location information to non-anchor nodes via iterative trilateration.
- Estimated ranging distances are compared with distances between known locations from GPS to provide a measure of ranging error (may be used for calibration).

As resources move in time and space, positional information propagates from virtual anchors to their neighbors, and on into the rest of the network as follows:

- For each epoch, new set of virtual anchors are selected based on role, mobility, connectivity and geometry (information in the SVT).
- Anchor nodes propagate location information to non-anchor nodes via iterative trilateration.

eLNS performance can also be improved by availability of INS dead reckoning by providing short term accuracy for Virtual Anchors while moving. Error accumulation can also be bounded by periodic synchronization with PLs or CMR beacons when and where available. In addition, Landmarks will be used to update/fix absolute position when and where available.

Auxiliary data sources, if available, also provide absolute position via Pseudolites and CMR's beacons to bound position errors for outdoor nodes. In addition, Landmarks are used, where and when available, to manually update/fix absolute position for outdoor nodes.

As team members converge on a building or a cave, several members are placed outside and act as reference anchors to extend absolute position information for the members inside the building/cave. Hence, absolute positioning could be present in all scenarios/environments.

For both outdoor and indoor scenarios (cave-like and in-door structures), a complementary Ranging/INS approach is employed where TOA ranging is used for periodic re-calibration of the INS system to be used (also to feed back to TOA) when TOA is poor. Several PDR mechanization techniques are also employed to improve the performance of the INS system for different movement patterns (walking, running, sideways and crawling) required for indoor operation. These techniques are described in Section 2.1.2.

To achieve that, we employ two innovative techniques. These are:

1) Node role change scheme to best match application/mission needs, network dynamics, and terrain conditions
2) State Vector Table (SVT) to monitor node/network status and error budget to achieve the required SEP accuracy.

In our system, node role change works as follows. Up to 50 nodes are created equal but they may assume different roles as needed including:

- 40 field nodes (up to 13 will act as anchors or common ranging partners for the clique)
- One cluster leader (part of the 40 field nodes)
- 4-10 nodes that will act as field nodes for dismounted resources attached to the platoon (over the normal 40 soldiers), beacons, or relays

While all field nodes are mobile, anchor nodes are stationary or least mobile. Anchors are elected periodically based on least amount of recent mobility, geometry, role and FOM (Figure of Merit) in estimated position. Anchors are assumed to have absolute position (at start of 8-hour mission) and the most accurate position at any given time. Up to 3 Field nodes may act as auxiliary data relays when in an underground or cave-like setting.

Table 2 - State Vector Table (SVT)

Application / Mission Data
Routes
Neighbors / Anchors
Node Role
Node Mobility
Node Position
Sensor data (FOM, Timestamp, etc…)

The State Vector Table maintains a data base on all relevant information that the node has about itself, about its locality/neighborhood, and about the application/mission (Situation Awareness, SA) information. This database is updated after each transaction including: after node movement, after a network event (such as node joint or depart), and/or after every mission/application event. The structure of the SVT is shown in Table 2.

We envision 3 distinct states for system operation. These are described in Table 3 along with SEP error allocations and budget estimates for each state and/or for different terrain types.

In the first state, **Deploy/Set-up**, resources are transported via air or vehicle to boundaries of AO where absolute position is derived via GPS or Landmarks/Maps. At that point, CMR beacons may be set up as an auxiliary data source to provide absolute position in the AO.

In the second state, **Approach/Re-organize**, resources converge towards the target structures (buildings or caves). During this state, mobile nodes will continuously update their SVT as they move and discover new neighbors. At some update rate, each node will elect and range with 4 other nodes (elected as virtual anchors based on a number of factors including geometry and mobility). The node will next use these ranging/TOA measurements to determine its position using trilateration. Alternatively, nodes may obtain position information from auxiliary data sources including two CMR beacons at the boundary of the AO and/or Pseudolites transmitters available at bases surrounding the AO. The allocated error budget for this state is 15 meters SEP and the update rate is once per minute. In addition, Landmarks will be used to manually update/fix absolute position when and where available.

In the third state, **Execute/Assault**, resources execute mission. During this state, nodes use the complementary approach combining INS and TOA to determine their positions. The allocated error budget is 10 meters SEP and the update rate is once per minute of faster. Thus, the total error budget is bounded to 25 meters SEP throughout the mission.

Table 3: System States and Error Budget.

State	Terrain	Coverage / Range	Technology	Anchors	Update/ Fix rate	Allocated Error (m) SEP
Deploy/ Set-up: Resources are transported to AO via air or vehicle, set-up CMRs fixed beacons	Open terrain	At base or boundaries of AO	GPS/Maps	None	Once per 8-hour duration	0 All nodes start with same error
Approach/ Re-organize: Resources move towards target structures, Nodes elect new set of anchors based on mobility, geometry, and role	Urban terrain	Up to 10 Km for CMR beacons and up to 100 meters for Virtual Anchors	Pseudolites Landmarks TOA	PLs and/or CMR beacons Alternatively, Virtual anchors can be used for NLOS conditions	Once per minute	15
Execute/ Assault: Resources execute mission	Cave-like and in-door structures	Up to 100 meters for virtual anchors	INS and TOA	Virtual Anchors placed outside structure And/or up to 3 relays inside the cave-like structure	Once per minute or faster depending on RSSI and FOM	10

In summary, our approach for GPS-denied navigation is based on the integration of TOA ranging and mechanized PDR to minimize localization error as well as the use of auxiliary data sources when and where available to bound positioning error to 25 meters SEP. Our eLNS approach is an analogue for USMC operational tactics which rely on coordinated mobility v. random mobility - this is how/why our approach (combined INS/TOA/eLNS) "just works" for USMC missions. This approach is detailed in the following sections.

2.1.2 INS Positioning

Inertial Navigation System is a set of self-contained navigation sensors. The term "self-contained sensors" indicates that sensors used in this system are inherently independent of other sources of positioning such as maps, GPS, LORAN, Pseudolites, etc. Combination of the following sensors is used in typical INS systems – tri-axial accelerometers, tri-axial magnetometers, tri-axial gyroscopes, and barometer. The accelerometers sense movement in the three axes; magnetometers sense the direction in three axes; gyroscopes sense a change in angular velocity along the three axes; while the barometer senses the altitude. The measurement from these sensors is fused and the technique implemented for this sensor fusion is the INS mechanization.

The most popular mechanization is the traditional INS mechanization wherein an accelerometer signal is double integrated to yield relative position and the Kalman filter functions as the integration tool. The main problem with this approach is the requirement of frequent absolute updates due to growth of errors with respect to time. As an alternative to the exponential error growth the traditional mechanization experiences, the Pedestrian Dead Reckoning (PDR) mechanization has been studied widely (Levi and Judd, 1999; Ladetto, 2000; Ladetto and Merimond 2002; Jirawimut et al., 2003).

In PDR, instead of double integrating the acceleration signals, they are used to count "steps". Each "step" is modeled using a standardized, static distance value based on physiological models. The distance traveled estimation using the static step length model is combined with the direction or heading provided by a gyroscope. Each position estimated in this fashion is added to the preceding position; hence the term dead

reckoning. The largest advantage of this relatively new mechanization is that it enables pedestrian positioning using low-cost Micro Electro-Mechanical Sensors (MEMS).

Three major problems of PDR in personal positioning exist. Firstly, the mechanization is typically only applicable for forward walking motion. Thus, the model fails if motions other than walking are encountered and/or the direction of travel is not in the forward direction. Secondly, the static step model does not support different physiological models and is not adaptive to changes in velocity. Thirdly, the system is susceptible to heading drift. The navigation system's definition of heading degrades after a few minutes due to gyroscope bias drift and loose or improper mounting/calibration of the device on the navigating personnel. To address the direction of travel, step estimation and heading complications, several variations to previous PDR approaches will be implemented.

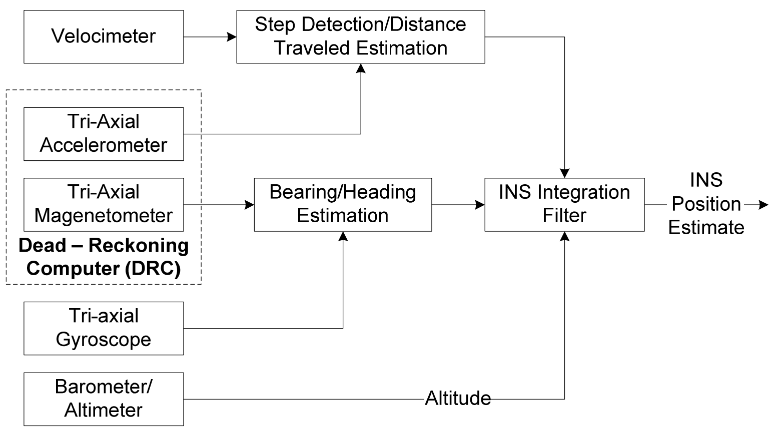

Figure 2 – Inertial Navigation System Application.

Our approach for using the self-contained inertial navigation sensors is presented in the figure above. To facilitate the reduction in the integration effort involved in Phase II, INS positioning devices available on the market will be utilized. A readily available example of such a device is the Vectronix Dead–Reckoning Computer (DRC). The DRC consists of a tri–axial magnetometer, a tri–axial accelerometer and a micro-controller. The DRC uses PDR–type mechanization for step detection and heading determination. More details on the DRC are provided in Section 3.4.1.

The INS mechanization is summarized as follows. Spikes in vertical acceleration are sampled to detect a step. The interval between two acceleration spikes is assumed to be the step. A Doppler radar based velocimeter is used to measure the velocity within this interval. Acceleration data can be integrated over the step duration to provide another reference for sampled velocity. By comparing the two sources of velocity, best velocity estimate can be obtained, leading to best distance traveled estimate by integrating the best velocity estimate. The gyroscope and magnetometer units are integrated to estimate the bearing.

The resulting distance traveled and heading estimates are combined with altitude information provided by the barometer to produce a relative position in 3 dimensions (x, y, z axes). If needed, a coordinate transformation may be applied to convert the relative position into an earth-centered, earth-fixed reference frame based on the WGS-84 standard. Finally, the relative position is added to the initial/previous position to provide an estimate of the current position.

Additional work is being done by Vectronix, for the Land Warrior Program, to further improve the accelerometer sensor performance of the DRC in order to more accurately detect a variety of motions beyond forward walking, including sideways and backward motions. For example, an autonomous step-scale and misalignment calibration (Helmert Calibration) has been developed. We expect to receive new DRC systems, with enhanced motion detection, in the next 60 days.

The heading measurement based on magnetometers is inaccurate in presence of external magnetic fields. Such magnetic interference is commonly observed indoors due to steel structures and stray magnetic fields setup due to power lines. To overcome this disadvantage in magnetometers, heading measurements are augmented by the integration of a tri–axial gyroscope. The gyroscope performance will make the device more reliable for indoor navigation, while the magnetometer and gyroscope will determine heading information for outdoor navigation.

As mentioned earlier, gyroscopes inherently suffer from a bias drift over time which results in degrading heading determination. To overcome accumulation of position error over time, the gyroscope needs to be updated periodically. Such updates are termed as Zero Updates (ZUPT). In (Ladetto and Merimond, 2002), gyroscope drift is reduced by ZUPTing the gyroscope to align with the magnetometer. This ZUPT assumes that the magnetometer is accurate. However, if the magnetometer reading is erroneous (as often observed inside buildings due steel structures and power lines), the heading errors are further compounded. A novel scheme for zero updates (ZUPT) of the gyroscope is to update the gyroscope of zero angular velocity in all three axes, when velocity of motion (obtained via velocimeter and integrating accelerometer data) is found to be zero. This scheme for ZUPT removes the dependence of the gyroscope on the magnetometer.

A novel scheme for improving step detection, heading measurement and attitude measurement error correction has been proposed in (Kourogi, et. al, 2003). This scheme makes use of accelerometer data along vertical and horizontal axes to determine step taken. The heading information is also complemented by comparing horizontal acceleration with the magnetometer and gyroscope heading measurement. This analysis is termed by the authors as Principle Component Analysis (PCA). As a production stage effort the PCA approach can be explored to improve step as well as heading detection.

Despite the aforementioned efforts to establish and maintain an accurate position estimate via the INS, the sensor's operational time is limited. As a result, the INS sensor will be monitored for reliability. When it is determined that the INS does not meet the required accuracy levels, the TOA component will be called upon to reset the INS.

2.1.3 RF Ranging/TOA Localization

The RF Ranging / TOA Localization sensor is based on TOA ranges provided by the ITT Clique Member Radio (CMR) (functionality described in Section 2.2.6), and the position information obtained during system initialization and provided by the INS sensor. The CMR is a combined ranging and data communication platform. The RF ranging feature provides a range estimate between ranging partners.

Using the ranges provided by these partners (also termed anchors) and their positions, trilateration can be used to compute the position of the fourth node. The anchors may be stationary (leading to better accuracy) or mobile (closer to application in this BAA, but leading to poorer long-term accuracy). This technique is similar to that used in the GPS system. The method of trilateration will be presented in Section 2.1.3.1 (Referential Coordinate System).

2.1.3.1 Referential Coordinate System

The referential coordinate system is intended for the situation where personnel cannot locate themselves via any form of absolute position. In such a situation, the need is to initialize a local map that will provide local positions of personnel in the field and ensure that personnel can track each other in any scenario.

Hence, a local map is established by initializing a local coordinate system (LCS), as presented in the Self Positioning Algorithm (SPA) (Capkun, et. al., 2001), with the team leader as the origin (INS systems initialize as (0, 0, 0)). With this origin, the leader ranges with two personnel in the team. One is located, arbitrarily, on the X-axis forming the LCS, and the coordinates of the second are computed. This scenario is depicted in Figure 3. This process is called *triangulation*. With the establishment of three anchor nodes, further nodes can be localized using *trilateration*.

The coordinates (x_2, y_2) are computed using **triangulation** as –

$R_{12} = \arccos\left(\frac{r_{01}^2 + r_{02}^2 - r_{12}^2}{2r_{01} \cdot r_{01}}\right)$, $x_2 = r_{02} \cdot \cos(R_{12})$, and $y_2 = r_{02} \cdot \sin(R_{12})$.

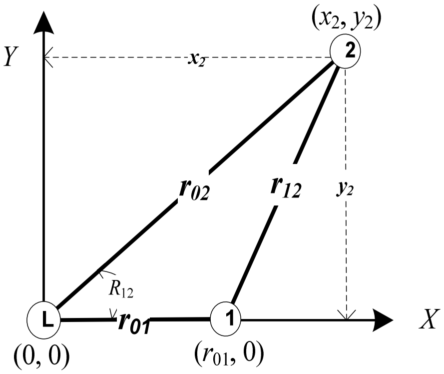

Figure 3 – Formation of Local Coordinate System (LCS).

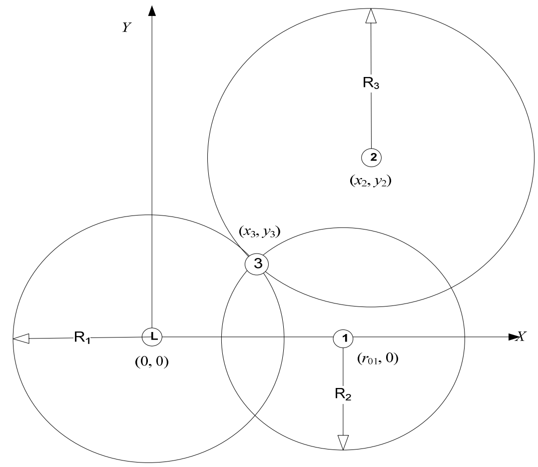

Figure 4 – Generic process of trilateration.

Similar to triangulation, **trilateration** (Figure 4) requires one of the anchors to be functioning as the origin and one anchor functioning as the X-axis. The equations for circles with radii R_1, R_2 and R_3, and to compute the coordinates (x_3, y_3) are as follows –

$R_1^2 = x^2 + y^2; R_2^2 = (x - r_{01})^2 + y^2; R_1^2 = (x - x_2)^2 + (y - y_2)^2$, and

$$x_3 = \frac{R_1^2 - R_2^2 + r_{01}^2}{2r_{01}}; \text{and } y_3 = \frac{R_1^2 - R_2^2 + (x_3 - x_2)^2}{2y_2} + \frac{y_2}{2} - \frac{2x_3^2}{y_2}.$$

The above equations for triangulation as well as trilateration compute position in 2D. However with barometer providing altitude data and RF–based ranges available in 3D, the range information can be decomposed in its components along the three axes. This compensation will result in modifications to the above equations, and provide a solution for 3D TOA position.

The above process initializes a LCS for any rank. However, the goal is to enable all personnel deployed to locate each other. Hence, a coordinate system needs to be established across the ranks – termed as the Network Coordinate System (NCS). If the platoon leader is the one that is performing the above steps, then the LCS will be the Network Coordinate System. However, assimilation of coordinate systems for all personnel should be possible to maintain the best possible relative position estimate. The assimilation criteria are broadened to three parameters –position Figure–of–Merit (FOM), connectivity (greater connectivity provides better chance of clique assimilation) and finally rank of coordinate system leader. The process for initialization, maintenance and assimilation of LCS to NCS is presented in Figure 5. The assimilation process is further elaborated in Figure 6.

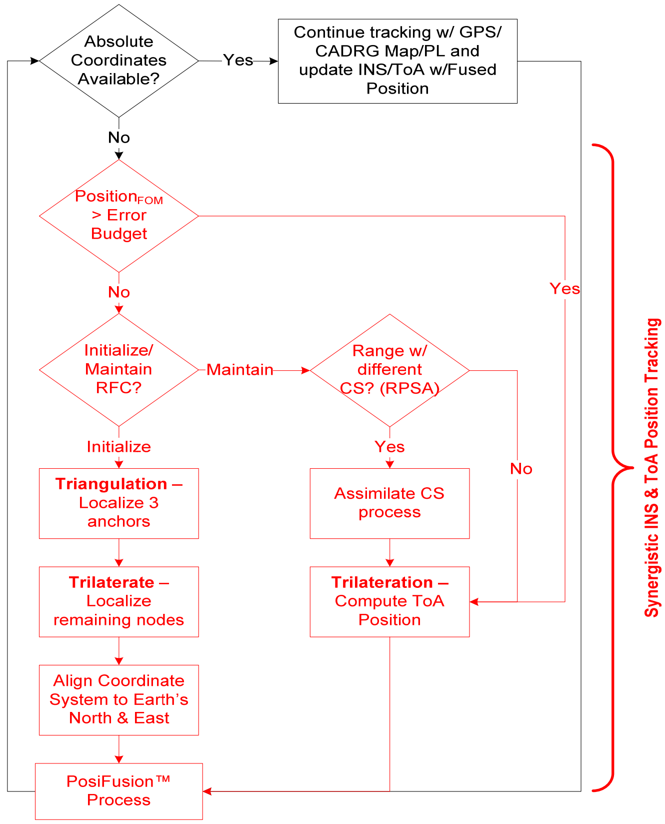

Figure 5 – Initialize, Reinitialize and Maintain Referential Coordinate System.

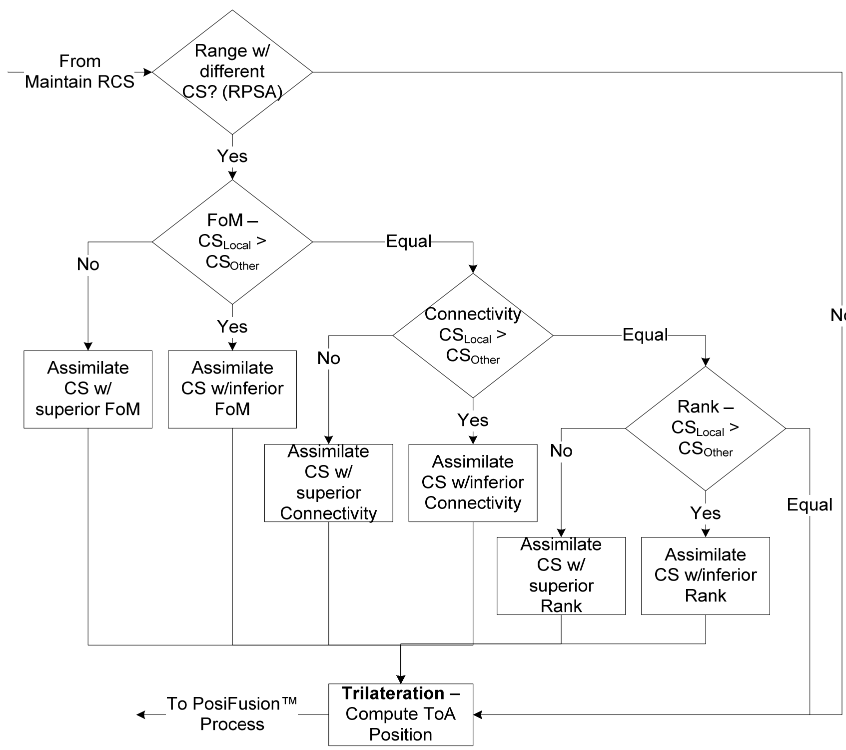

Figure 6 – Referential Coordinate System Assimilation Process.

2.1.3.2 eLNS and Iterative Positioning Algorithm

TOA based positioning system is based on TOA ranges provided by the CMR. The CMR will be a combined ranging and communications platform. The radio will provide slant range between ranging partners. The clique member position may be computed in 3D using the position and slant ranges of at least three partners and integration of the clique member's altitude (if prior position is known). Based on the slant range provided by these partners (also termed anchors) and their positions and the altitude of the un-localized node, trilateration can be used to compute the position of the un-localized node as described below.

To help improve clique navigation accuracy, the CMR beacons can be set up at known positions at the AO boundaries to enable AO wide reachback from mobile radios to the CMR beacons; however, line of sight (LOS) to the CMR beacons will be required. If CMR beacons cannot be used for a mission, or if LOS cannot be maintained, eLNS (extended Leapfrog Navigation System), a distributed algorithm based on LNS (Leapfrog Navigation System) algorithm will be used to distribute absolute position information throughout the network in time and space. The LNS algorithm was developed as a solution for localization and navigation for the Mars rovers. In simulation and actual tests, LNS demonstrated the capability to enable navigation over a 15Km distance with 10m accumulated CEP without an absolute position reference during clique navigation.

In eLNS, nodes have two modes: localized and un-localized. In localized mode, nodes have known locations and may act as virtual anchors (VAs). VAs may be beacons, fixed or mobile anchors. Periodically, they broadcast their position information to other members of the clique. In un-localized mode, nodes have unknown locations. They localize themselves as follows:

- Listen for broadcast
- If broadcast from one localized node at (x, y, z) heard:
    - Determine distance to localized node at (x, y ,z) via TOA ranging.
- If broadcasts (from three or more other localized nodes) heard:
    - Select best VAs from list of ranging partners
    - Determine distance to VAs via TOA ranging
    - Determine own position via trilateration
    - Switch to localized mode.

Nodes then wait for the next epoch (leapfrog distance or time) to repeat this positioning process as depicted in the figure below.

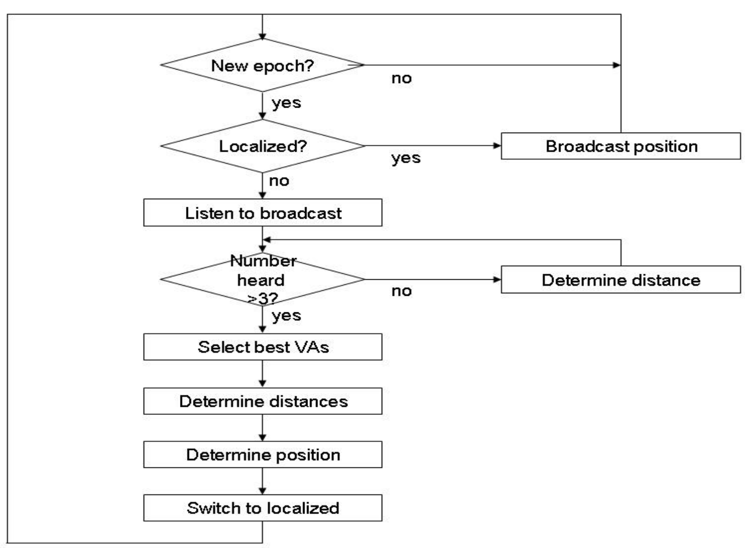

Figure 7 – Iterative Positioning Algorithm.

Temporary virtual anchors are also used to overcome the scarce anchor problem; that is when an un-localized node has fewer than 3 reference anchors within its reach. In that case, we assume that the un-localized node has at least three 1st hop neighbors where each will also have at least three 1st hop neighbors. When some of those neighbors reach three localized nodes, those will be used as reference anchors to compute their positions. Those neighbors can then be used as virtual anchors to the un-localized node. Since the un-localized node will have more than three 1st hop neighbors, given that TOA range is 2Km, it will end up with many more position estimates. An optimization process will be used to select the one with the least accumulated position error. This process can be described as follows:

- Participating nodes in this protocol are described as nodes that are either located (anchors) or un-located (unknowns) with three participating neighbors.
- Set up error equations between every participating node and anchor, and between every two participating nodes resulting in $2*i*U_i$ unknown values (the x and y of every unknown node U_i, i=0, … N; N= is the number of un-located nodes).
- If we have enough independent equations (that is enough known anchors), we can solve for all the U_i nodes.

2.1.3.3 Secure Localization

RF ranging/TOA location technology, provided via the CMR, is based on a direct sequence spread spectrum (DSSS) waveform with embedded transmission security (TRANSEC). The RF ranging/TOA location technology uses the same carrier sense multiple access/collision avoidance (CSMA/CA) protocol for channel access as used when communicating. The DSSS waveform, the layers of the CSMA/CA protocol and the protocol for two-way RF ranging/TOA are not vulnerable to wormhole or sybil attacks. The spurious packets generated by wormhole/sybil attacks will be ignored by the network because these packets will not have the latest DSSS code provided by TRANSEC. If the enemy determines the current DSSS code from TRANSEC, the network will ignore the spurious packets generated by wormhole or sybil attacks because various network timeouts will occur if proper packets are not received in proper sequence, causing the protocol to continue normal network maintenance, communications, or ranging. In addition, because the RF ranging protocol employs a 5-way handshake mechanism, an enemy would require detailed knowledge of the ranging algorithm in order to produce a packet that would not be summarily discarded.

Detailed information on the communications and security aspects of the government validated SRW waveform can be requested by ONR from the JTRS Joint Program Office.

2.1.3.4 Position Sharing/Communication

The CMR also provides communications and ad hoc networking. In addition, the CMR running SRW 4.8Mcps EW Mode will be used as the standard military radio to reach back to headquarters, as mentioned during our interim progress review at ONR. Our baseline concept could also easily include interfacing to SINCGARS or EPLRS variants to handle the reach back function.

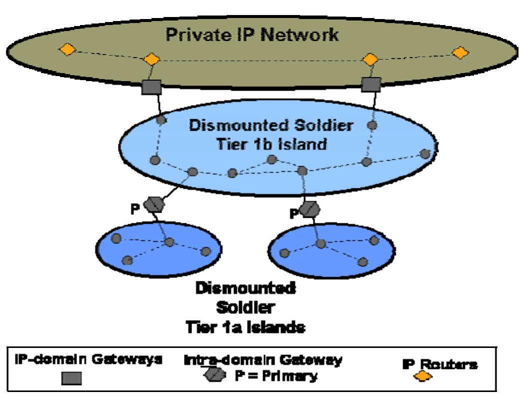

Figure 8 – CMR Network Structure

The CMR provides a transparent, self-organizing network that hierarchically organizes into two levels as shown in the figure above. Each level is composed of tiers. Tier 1a islands are composed of individual nodes. One member of the tier 1a island is selected to be the Island Head (IH) administrator. The IH controls island formation and is the primary gateway to tier 1b. Tier 1b is composed of mostly 1a IHs. The tier 1b island also has an IH. Tier 1b islands have members that are gateways to the private IP network. The network to support 50 clique members will in general be contained within a single tier 1a island. An IH will be selected to be the primary gateway back to headquarters through any relays that are available, when needed.

Prior to mission start when the clique members power up their CMRs, neighbors are discovered using Packet Radio Organization Packets (PROPs). PROPs are transparent to the user and are sent periodically after initial power up. The network will be formed and reformed as a result of the information resulting from the periodic PROPs. Once the network is formed, Link State Advertisements (LSAs) periodically send routing information to the network nodes.

When a clique member has a message to send, the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) Media Access Control (MAC) protocol is used consisting of four packets. The message sender initiates the process by sending a Request to Send (RTS) indicating the destination of the message. The destination node replies with a Clear to Send (CTS) if the RTS is properly received. The message sender then sends the message packet(s) and the destination node replies with an Acknowledgement (ACK) if the message packet is properly received. If the ACK is not in the proper slot, the process will repeat up to N times where N is configurable and generally set equal to 2.

CMR communications is based on SRW 4.8Mcps EW Mode. This is a direct sequence spread spectrum waveform with a chipping rate of 4.8Mcps. Data rates are automatically throttled between 18.75kbps – 900kbps depending on propagation conditions. A RAKE equalizer is employed in the receiver for multipath mitigation. NSA Suite B security is included along with TRANSEC that is applied to several of the waveform parameters. More detailed SRW information can be requested from the JTRS JPEO.

As network node, CMR beacons can also be used to relay message between the AO and headquarters.

2.1.4 TOA-INS Integration and Multi-Sensor Fusion

The most critical design aspect for this BAA is design of the fusion algorithm – the ability to fuse position information generated by various position sensors. The approach for position fusion called the PosiFusion™ algorithm is illustrated in the figure below. The approach will model the position information generated by several position sensors and will apply a Kalman filter to integrate the position information.

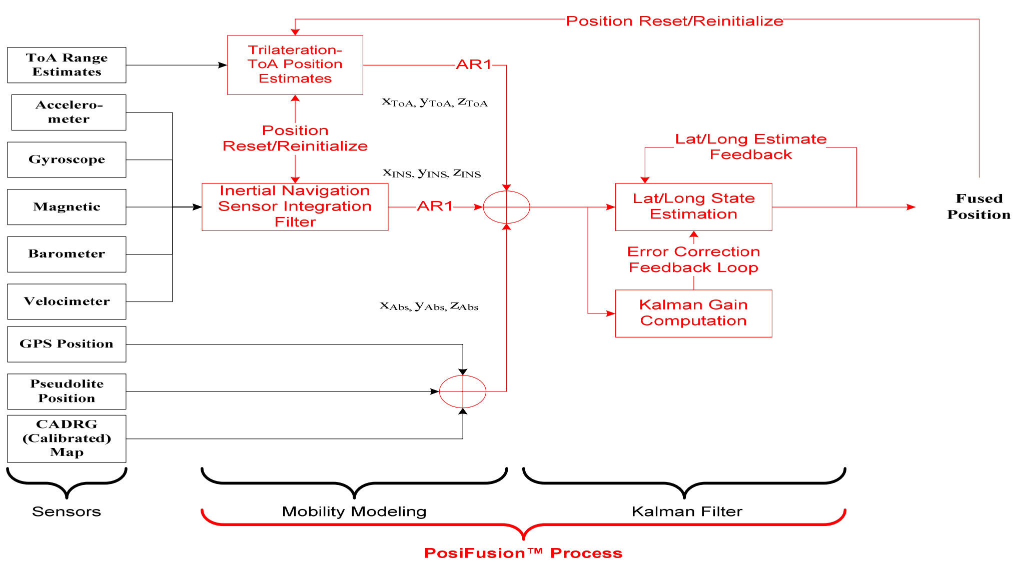

Figure 9 –Position Fusion Algorithm.

Every position sensor makes use of different physical phenomenon in order track current position and the associated SEP. Each positioning system such as INS, TOA and GPS carries forward errors – INS position has errors due to sensor drift, GPS due unavailability of satellites, TOA position due errors in range information or unavailability of sufficient number of reference nodes. Mitigation of errors in INS position has been discussed in greater detail in Section 2.1.2. The SEP associated with TOA position is primarily defined by standard deviation of TOA range information and number of ranging partners (reference nodes) available. The best possible ranges are made available via filtering processes termed Ranging Partner Selection Algorithm (RPSA)/TOA Ranging Partner Selection (TRPS) (algorithm to select best ranging partners) and TOA Data Screening (TDS). TDS algorithm flowchart is depicted in the adjoining figure is a periodic process that is initiated by the reception of the Range Data message.

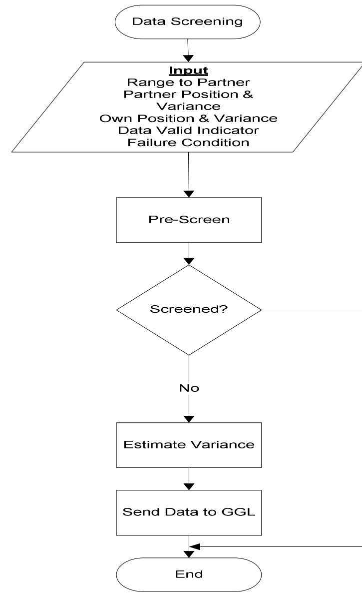

Figure 10 - TOA Data Screening algorithm.

Modeling the position streams provides the PosiFusion™ process a universal platform for fusing position information available from disparate sources. This modeling of position of each position sensor is termed as mobility estimation. The most significant advantage offered by mobility modeling is modeling position error for every sensor platform. The SEP of the fused position is an output state of the position fusion Kalman filter, and accurate noise modeling allows position fusion with least possible SEP.

The mobility models have been designed as Auto–Regressive (AR) processes. An AR process is linear regression of previous states of a function over itself (hence auto). A sample AR process, x_k, can be given as: $x_k = \Phi_k . x_{k-1} + \eta_k$ – where Φ_k is the regression filter coefficient, and η_k is noise component. This AR function is termed as the AR1 or AR (1) process indicating that the filter is of *order* 1, i.e., value of function x at instant k depends only on its previous value, x_{k-1}. Mobility modeling for Vectronix DRC and CNM was performed and found to be AR1 (refer to Section 2.3.5). Noise modeling using AR processes was published in (Nassar and Naser, 2004)

Finally, the modeled estimates of positions are provided to a Kalman filter for fusion. This is a closed loop system – a system where the feedback is position estimate with least errors to ensure that the errors remain bounded. The feedback can also be used to reset/reinitialize the position information of the INS and TOA.

The complimentary approach between INS and TOA is also employed where:

- Dead Reckoning is used to remove ambiguity in the TOA SEP when INS FOM is high while INS sensors are reinitialized after each TOA position estimate.
- TOA is used to initialize INS during localization and to reinitialize INS when INS FOM is low.
- In addition, TOA and INS sensors are initialized/re-initialized after any absolute position fixes.

In this approach, feedback between sensors improves performance (especially in cave-like and indoor scenarios) and more accurate position information is provided than would be possible by averaging independent TOA and INS sensors:

- Periodic recalibration of INS via TOA improves the INS solution
- INS generated solutions when TOA is poor feed TOA, making the node a better ranging partner and providing a better TOA position

When absolute position is not available, INS and TOA are used to track personnel on the calibrated map. Position updates from INS and TOA are then fused as shown in the adjacent figure to minimize the errors in position. The INS gyro has the tendency to drift with time resulting in heading errors resulting in position errors. To overcome this INS needs periodic reinitialization. The reinitialization is of two types – the first is the ZUPT where only the gyro is reset to the magnetic compass to prevent further drift, and the second is the position reinitialization where the INS position is reinitialized to a position derived by the PosiFusion™ filter.

In absence of absolute position fix, the TOA positioning system relies on the INS for position fix. Hence, the accuracy of TOA positioning is correlated to the position accuracy of INS position. However, if the TOA position FOM, defined in the error budget, is better than INS position FOM, the TOA position may be used to reinitialize the INS. Hence, the TOA and INS positioning systems form another closed loop system.

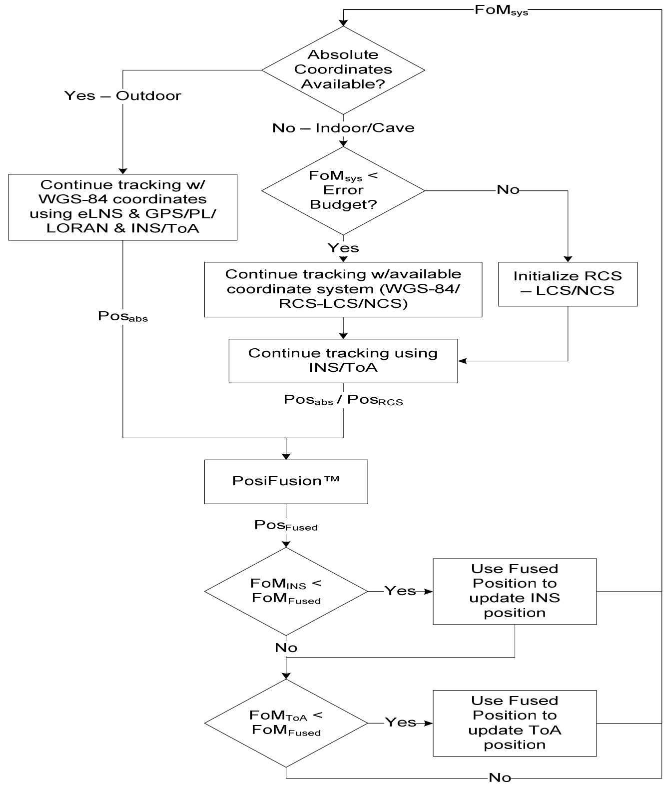

Figure 11 – INS & TOA Complementary Positioning System.

The figure above illustrates how all available sensors are used to ensure that system provides at least relative position under all circumstances. In presence of absolute position, INS and TOA sensors are not needed for tracking, however the sensors are updated with absolute coordinates available. The available coordinates are fused to ensure the correctness and the fused absolute position is used to update the INS and TOA sensors.

In absence of absolute coordinates, the INS and TOA systems attempt to track position using the last updated absolute coordinate system. Extending the time over which the INS and TOA systems can track position accurately is an optimization problem that will be solved during Phase II. However, in presence of hostile environment such as presence of strong external magnetic fields or severely RF challenged terrain one or both sensors can be rendered useless. In such situations, it is recommended to reinitialize to a relative or referential coordinate system so that relative position error is reduced to zero. After initializing a referential coordinate system (RCS) – either local coordinate system (LCS) or network coordinate system (NCS) – INS and TOA track changes in position.

The position changes tracked by INS and TOA are fused to ensure the error budget is maintained at all times. Instead of having several small LCSs operating in field, assimilation of CSs of different teams to form a NCS is preferred to ensure all members of the deployed team can track each other. This process of assimilation was illustrated in Figures 5 and 6 (Section 2.1.3.1). The assimilation process is based on three criteria – (1) mean FOM of position of a CS, (2) connectivity of a CS, and (3) Rank of personnel heading the CS.

2.1.5 Auxiliary Data Sources

2.1.5.1 CMR Beacons

The concept for determining absolute position while navigating in urban areas is shown in the figure below.

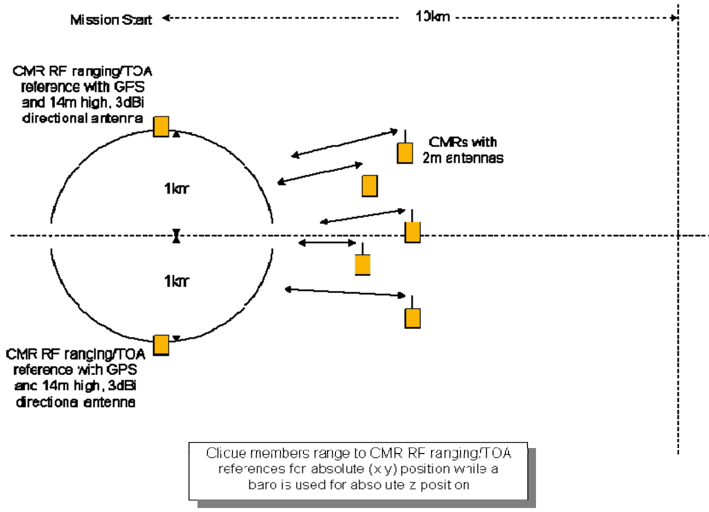

Figure 12 – Using CMRs as auxiliary data source for absolute position information.

As shown, two CMR references may be placed at the mission start location for use during absolute horizontal positioning when RF ranging. A barometer will be used for absolute vertical positioning because in order to achieve reasonable VDOP for RF ranging, a CMR would have to be mounted at a height. If mounted at 14m high and using 3dBi directional antennas facing the mission area, the CMRs will enable RF ranging coverage for the Area of Operation. The link budgets in Figure 13 below show that clique members will be able to reach back to these references throughout the entire 10km mission. Above figure shows that with a path loss of 165dB and an HDOP of 3.6 the CEP = 13m at 10km from the CMRs left at the mission start. HDOP and VDOP to follow were derived from (Krauter, A., 1999) – the respective absolute (10km distance) and relative geometries depicted in the figures above and below. The path loss is comprised of 160dB of attenuation due to $1/R^4$ propagation plus an estimated 5dB of foliage loss at our 300MHz carrier frequency. Our RF Ranging/TOA techniques will ensure we achieve the CRB RF ranging accuracy with multipath present.

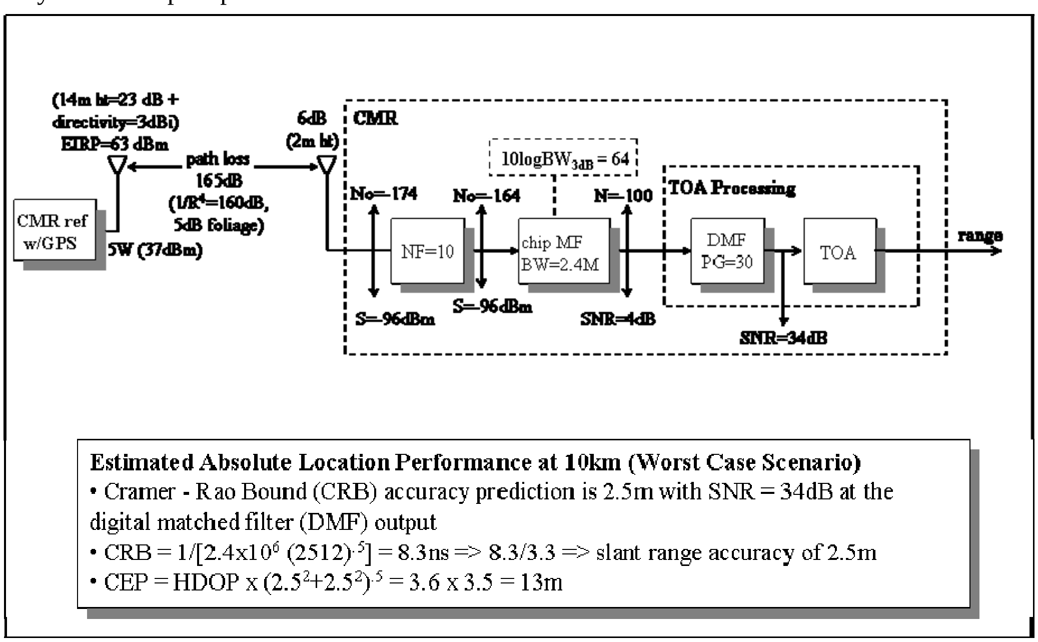

Figure 13 – Link Budget for Clique Member Ranging to CMR RF ranging/TOA Reference with GPS for BW=2.4MHz and Frequency=300 MHz.

2.1.5.2 Pseudolites (PLs)

PLs will be used to provide auxiliary data sources/beacons for location information as stated in the BAA. The iTRAX03 GPS receiver, included in our system specification, provides the capability to process L1 signals generated by low cost PL systems available from Space Systems of Finland. The Concept of Operations document describes how an array of these PLs will be used to provide wide area coverage, including initialization of the CMRs. PLs will be used to extend access to pseudo range/timing data within the operational area, thus extend the operational range of TOA/INS system.

Since PLs cannot provide absolute position in all areas and under all circumstances, our solution will work without any PL infrastructure but will work even better with PLs' infrastructure. For this purpose, 4 PLs transmitters can be placed at known locations (GPS/Loran or Landmark) and can provide absolute position reference from remote locations. The PLs can be placed as far as 70 Km from AO to act as beacons with configuration similar to that of the CMR beacons. The PLs can transmit their L1 signal at any frequency - if the L1 signal is not transmitted at GPS frequency, a frequency converter is needed.

2.1.6 Geo-Location Core / Integrated Single Board Computer (SBC)

Our approach to achieving the small form factor yet robust performance capabilities required for the ONR application incorporates a highly integrated, wearable computer system. The integrated system limits the need for manual interaction and will allow operators to maintain focus on their primary task, without sacrificing individual situational awareness for device operation. Multiple processing and interface platforms are provided to allow this unit to operate in real time with a high connectivity to position sensors, military radios, and host control and visualization devices.

The figure below illustrates the integrated Geo-Location core / SBC approach (dimension and weight estimates of the components are included). Tight coupling and system miniaturization is possible by integrating the primary INS, TOA and GPS components in a single housing. GPS reception and INS signal processing occurs in one multi-functional device, while allowing the remaining INS / TOA / GPS fusion, networking, visualization and human-machine interface (HMI) tasks to be handled by a separate processor. By distributing sensor fusion and interface tasks across two (2) processing cores, real-time performance is possible while maintaining low power consumption and low heat operation.

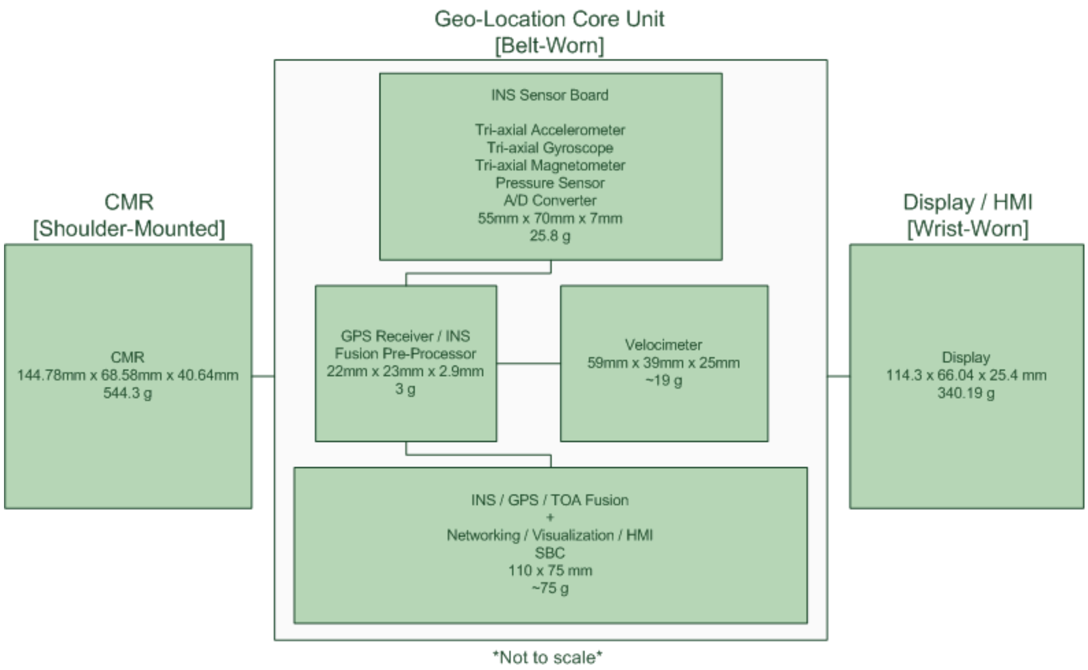

Figure 14 – Geo-Location Core / Integrated SBC Concept.

At the heart of GPS and INS processing is a GPS receiver and INS fusion pre-processor. This device will communicate with the IMU, velocimeter, and altimeter and combine the various sensor data with its inherent GPS signal data in order to form a single, accurate GPS / INS position solution. This device is extremely small (22 x 23 x 2.9 mm) and lightweight (~3g), yet capable of supporting the computational load required for the GPS / INS sensor fusion. The resulting position estimate of the GPS / INS pre-processor will be forwarded to the SBC component for further processing.

The SBC is also small (110 x 75 mm), lightweight (~75g) and capable of multiple tasks. As mentioned earlier, the SBC will receive pre-processed GPS / INS position estimates from the GPS / INS pre-processor. Once received, the position data will be combined with TOA data as presented in the Multi-Sensor Fusion section. A resident network (TCP/IP) stack will forward the fused position to other clique personnel via the Clique Member Radio (CMR). Finally, the fused result will be sent to the display component for visualization and shared situational awareness.

2.1.7 Position Visualization

The map screen (shown in figure below) displays the map selected by the user, a set of images that indicate 1.5 times the maximum effective range of the unit's weapons systems and provides icons for the local node user and all other resources with system nodes that are within range of the primary user's system. Here, we note that:

- Map will show 2D view of all clique personnel within 1.5 x weapon range
- Friendly personnel icon will appear as a blue circle with a notch oriented in the direction of the user's heading
- Friendly will have a 3-character ID above their icon
- The display component is NVG-capable and Sunlight readable
- 10x digital zoom
- Moving map-capable with north-up and heading-up modes
- Thumbstick control for map panning / cursor selection
- 3-button quick selection / activation options to speed common tasks
- The navigation system Figure-of-Merit (FOM) / accuracy estimate will be displayed
- The sensors used in navigation estimate will be displayed
- Map scale will be available
- A text messaging feature is available which features:
    - Message alert notification (vibration)
    - Configurable quick send messages
    - Manual acknowledgements can be activated for each message
    - Messages will be stored in log.

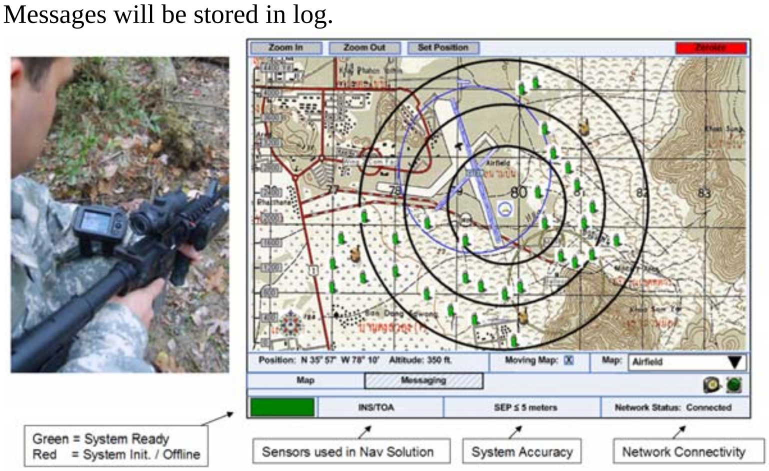

Figure 15 – 2D Visualization with concentric circles showing assets within weapon range.

3 Results of Required Studies

3.1 SEP Error Analysis

SEP Error Analysis was conducted for the assumptions listed in Table 4.

Table 4: Background Assumptions for SEP Error Analysis.

ONR SEP Analysis	Value	Units	Basis
Total error budget	25	meters	Based on BAA
Total Linear distance	10,000	meters	Based on BAA
Movement speed	0.35	m/s	Human Locomotion: walking @ 1 m/s and up to running @ 4 m/s Average speed is 0.35 m/s (10,000 meters over 8 hours)

<u>The following analyses show a point solution in our design space. Different choice of parameters may be used to demonstrate the robustness and range of our design</u>.

PDR Mechanization Error Analysis: For the INS Analysis, the following process was used:

1. Identify major contributors/error sources (found to be the step size and gyro)
2. Obtain nominal values (a nominal value of 18 deg/hr was used for the gyro and 10% initial error in the step size)
3. Calculate total error and required ZUPT rate.

A constant bias step-error model (Mezentsev amd Lachapplle, 2005) was used for this analysis, representing worst case scenario (Poisson and Gaussian models will yield better results). The resulting error was 10 meters over 80 meters of distance traveled (over 50 second intervals). We concluded that we can use TOA ranging to keep the INS error bounded (zero update the bias drift for the individual sensors) every 50 seconds to limit the error below allocated budget of, for example, 10 meters SEP over a distance traveled of 80 meters.

Analysis of major error contributors (step length error and heading error) based on the assumption that step size error and heading error are the major contributors of INS error see Table 5 for a complete analysis.

Table 5: INS Error Analysis.

INS Error Analysis	Value	Units	Short-range positioning in cave-like structures and in-door buildings
initial variance of constant step error (θ)	0.1	Meters	depends on uncertainty of user motion
Travel time	50	Second	Used to estimate fix rate to bound error
Estimated step size	0.8	Meters	depends on user motion
step count (N)	100		at constant pace of two steps per second for one hour walking
distance error after N steps (N θ)	10	Meters	Constant Bias Step Error Model is used for worst case
Estimated traveled distance = L	80	Meters	linear distance without gyro impact
heading drift during travel time = θ	0.00008276	rad/s	18 °/hr or 0.0000872 rad/sec
arc = R = L/ θ	966650.556	Meters	curve of maximum deflection from a straight line due to the gyro drift as a circle with a very large radius R.
distance error variance due to heading = R(1-cos θ)	0.0033104	Meters	
Total INS error due to step size and heading	10.0000005	Meters	
Conclusion: Use fix rate of about 50 seconds to bound INS error to allocated error budget of 10 meters for indoor operation. This can be achieved via TOA as described in Section2.1.2.			

Note: Other factors affecting this analysis include: sudden direction changes, different walking and running velocities, different surroundings (urban areas, forests, indoors).

eLNS Epoch Analysis: Using the assumptions listed in Table 6, an attempt was made to calculate the total error in propagating absolute position using the eLNS algorithm. The analysis shows that eLNS will result in a maximum error of 4.4 meter SEP over 10,000 meters of distance traveled (this analysis does not account for minimum error floor in TOA ranging). This is based on ranging distance of 80 meters with new positions determined every 50 seconds. This is much smaller than allocated error budget of 15 meters for outdoor operation

Table 6: eLNS Error Analysis.

eLNS Error Analysis	Value	Units	extended-LNS without restrictions on node mobility
Base distance			initial distance between nodes (irrelevant)
Leap distance	80	meters	traveling distance before next location/position determination
Number of leaps	125		Total linear distance/leap distance (also same as number of position estimates)
total eLNS error	4.41249334	meters	number of leaps * ranging error at leap distance
Conclusion: use leaps of about 80 meters			

Update Rates: Assuming two nodes moving at average speed of 0.35 m/s, the change in relative distance between the two moving nodes is 0.75 meter after one second or 45 meters after one minute. If LOS radio range for communication is around 25-100 meters (see below in relay analysis) nodes could communicate/range at rate of about once to twice per minute.

Relay Analysis: Relays may be used for non LOS cave navigation. In general, we expect that relays will not be needed for operation of 100m linear distance into underground or cave-like environments in the production system. It is estimated that the communication range is 25 meters when 3 relays are used and around 50 meters when only one relay is used. The range is 100 meters when no relays are used. This is shown in the figure below.

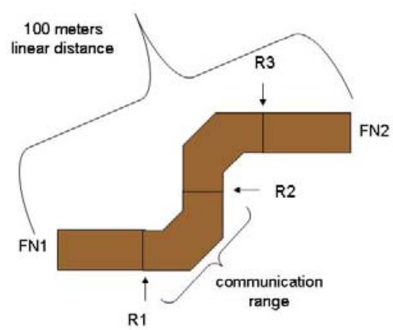

Figure 16 – Relay configuration.

3.2 TOA Link Budget/TOA Error Analysis

3.2.1 CMR Ranging Performance Analysis for Outdoor Scenario

The link budget for outdoor scenarios is shown in the figure below. This link budget clearly shows that the SEP error of 25 meters can be met with ranging at both 1 and 2 Km distances.

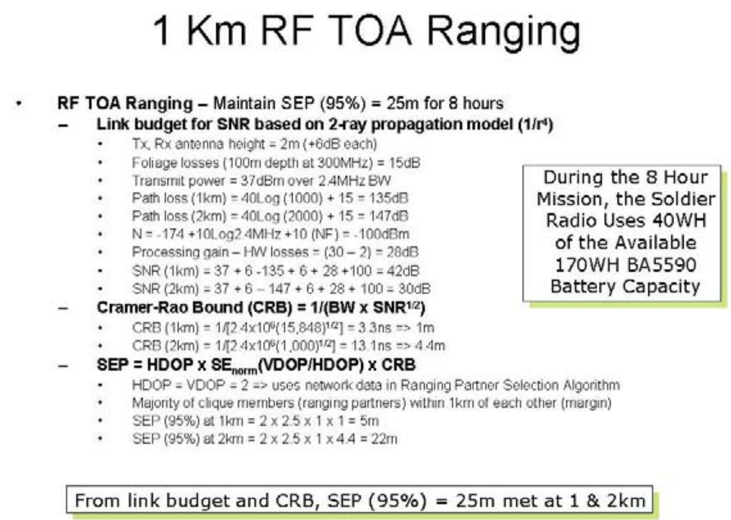

Figure 17 – Link Budget for Outdoor Scenarios.

3.2.2 *CMR Ranging Performance Analysis for In-Building Scenario*

The scenario used for analyzing relative position accuracy while navigating in buildings is shown in Figure 19. As shown, a 15-story building was selected for illustration with a single clique member in the building on the 15th floor. The clique member on the 15th floor is using 4 external CMRs as references for RF ranging to determine his relative position in 3-dimensions. Note that two of the external references are elevated at 3m to provide reasonable VDOP. Values for the propagation loss exponents, exterior wall penetration loss, and floor height factor were extracted from the literature with a bias towards worst case.

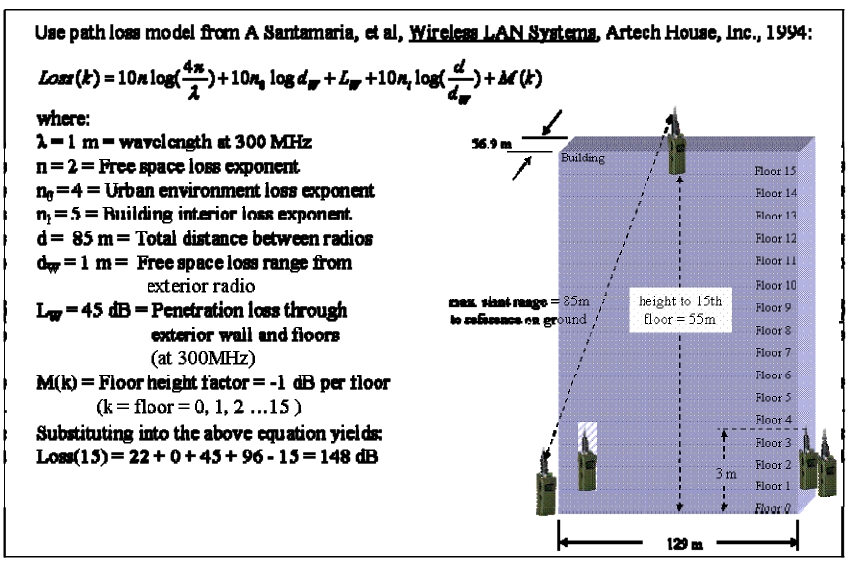

Figure 18 – Path Loss for Ranging From Building Fifteenth Floor (Interior) to Ground Floor (Exterior) With BW = 2.4MHz and Frequency = 300 MHz.

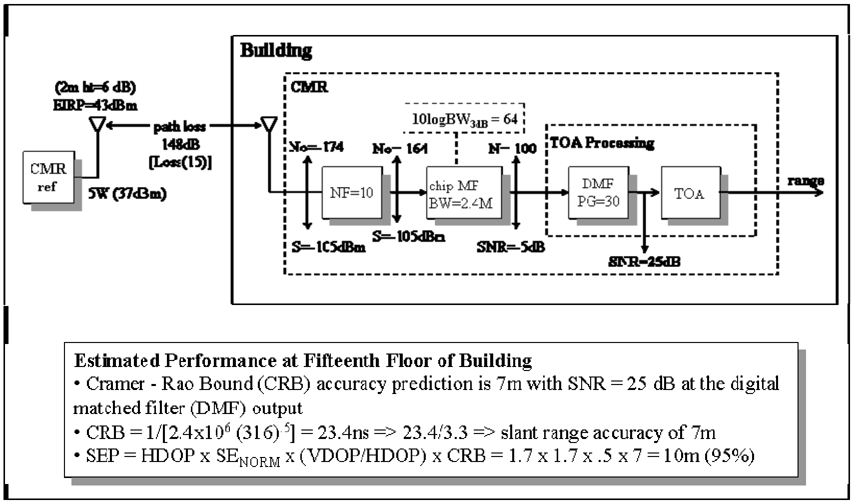

Figure 19 – Link Budget for Ranging From Building Fifteenth Floor (Interior) to Ground Floor (Exterior) Reference with BW = 2.4MHz and Frequency = 300 MHz.

Figure above concludes that RF ranging will provide a 95% SEP = 10m, for this illustrative example, exceeding the requirement of 25m SEP (95%). Figure 20 concludes that the interior CMR on the 15^{th} floor will communicate location data back to an exterior CMR (BER = 10^{-6}) at 225kbps. The exterior CMR will automatically relay the location data back to headquarters.

3.2.3 CMR Beacon Ranging Performance Analysis

The plots in the figure below show TOA location accuracy versus range, HDOP, and foliage depth. The TOA application is used to determine horizontal position by performing RF ranging, with TOA measurement, to two (2) references with an associated HDOP (assumed here to be from 1 – 4). Foliage attenuates the signal as a function of depth and the foliage isn't necessarily contiguous, for example, 100m of foliage could be spread over a 2km range. Note that best achievable TOA accuracy of approximately 1.5ns (estimated) limits CEP at the closest ranges, for example ≤ 4km range in the first figure (Foliage Depth = 25m).

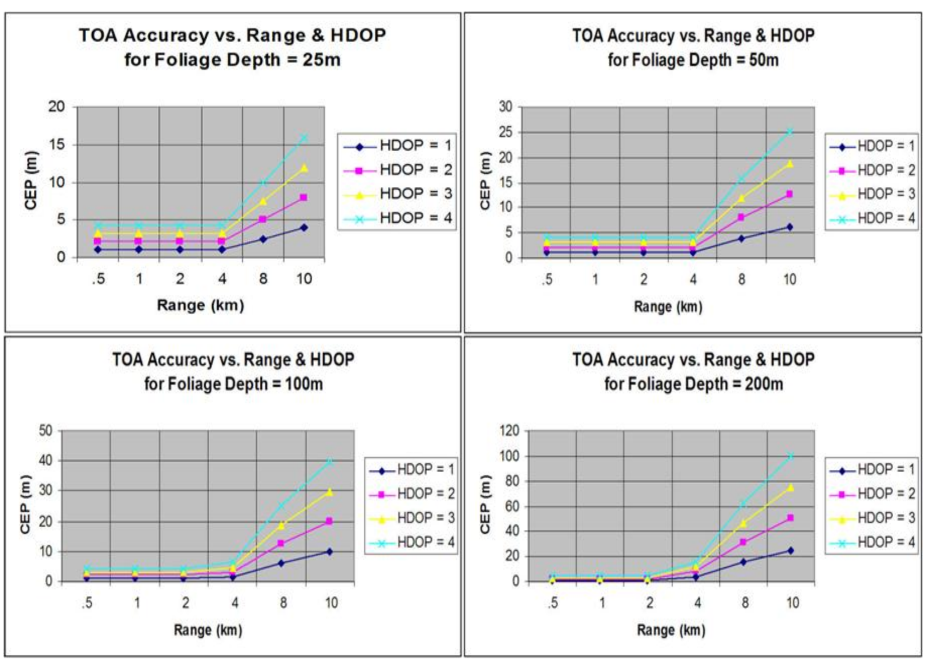

Figure 20 - TOA Accuracy vs. Range, HDOP and Foliage Depth

3.2.4 QMFR Analysis

The initial performance test of QMFR using a 32 MHz bandwidth occurred during SUO SAS Phase II (November 2000) of our TOA development and involved testing in the laboratory where multipath could be emulated in a controlled manner. During SUO SAS Phase II, the QMFR algorithm running did not run in the radio hardware and software making it necessary to use Logic Analyzers to capture the appropriate data from the radios for processing offline. Different length cables were used to connect two radios together, one cable to emulate the direct path and one cable to emulate multipath. The difference in cable length is proportional to the multipath delay being emulated. In line attenuators were inserted in each cable to allow adjustment of direct versus multipath amplitude. For comparison purposes, we tested single frequency non-QMFR TOA ranging algorithm under the same conditions. Table 8 summarizes the results of the testing. In the table, the Multipath Condition column lists the multipath delay and amplitude relative to the direct path, e.g. '15ns 8dB' corresponds to multipath that is delayed by 15ns relative to the direct path and 8dB stronger in amplitude. The entries in the 'Non QMFR' and 'QMFR' columns are the mean plus standard deviation of 10 trials. As shown in Table 8, QMFR achieved significant improvement over Non-QMFR for all cases.

Table 7: QMFR versus Non-QMFR: We use the mean plus standard deviation of 10 trials as the performance metric.

MULTIPAT CONDITION	NON-QMFR	QMFR
Direct path only	1.0ns	0.5ns
15ns 0dB	7.0ns	2.5ns
30ns 0dB	4.0ns	2.0ns
60ns 0dB	12.0ns	4.25ns
15ns 8dB	11.5ns	5.5ns

3.2.5 Cave Scenario

For operation in caves, experimental measurements in our recommended carrier frequency band shows that LOS and NLOS paths will provide coherence bandwidths of 4.3 MHz and 2.8 MHz respectively. The measured attenuation 100m into the cave was approximately 20-25 dB and the authors estimate location measurement accuracy of 5m.

This supports use of a 2.4MHz bandwidth; direct sequence spread spectrum waveform. Operationally, as shown in the figure below, we will be able to RF range and communicate from a CMR 100m into the cave to a reference at the cave entrance in order to determine location of the CMR in the cave. As shown, the CMR at the cave entrance determines self position using other external CMRs. The CMR in the cave ranges to and sends the resultant range to the CMR at the cave entrance. The linear cave requirement constrains the in-cave path to be linear, allowing a single slant range measurement to be sufficient. If necessary, we can populate the cave with up to 3 CMRs (or relays) that will be located relative to the reference at the cave entrance.

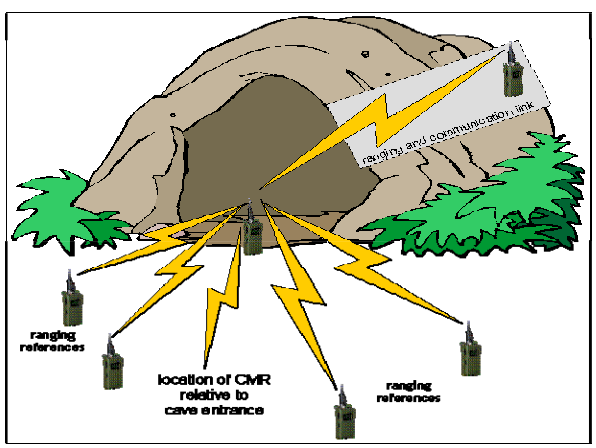

Figure 21 – CMR in Cave Ranges and Communicates to CMR at Entrance.

3.3 Mobility Estimation Analysis

Mobility estimation was introduced briefly in Section 2.1.6. It was mentioned that mobility estimation leads to better noise modeling. In this section we describe the process of mobility estimation and modeling; present mobility model for the Vectronix Pedestrian Navigation Module (PNM); and present conclusions based on the model. PNM is a Pedestrian Dead Reckoning system. Hence, the system estimates the current distance and heading and adds it to the prior position to obtain the estimate of the present position. Hence, correlation between consecutive positions is very high. Auto Regressive Moving Average (ARMA) models are based on similar principles.

The ARMA process integrates the correlation between positions with its AR component, while the errors inherent to the process are modeled as a moving average of the prior errors in form of the MA component. ARMA functions are denoted as ARMA (*p*, *q*), which is the combination of AR (*p*) and MA (*q*) where *p* and *q* are integers. AR (*p*) indicates that estimate of the present position is a significantly correlated regression of previous *p* positions; while MA (*q*) indicates error in the current position is a moving average of the error over previous *q* positions. The values of *p* and *q* are determined analytically. A generic ARMA (1, 1) function, x_t, can be represented as

$$x_t - \phi_1 \cdot x_{t-1} = z_t + \theta_1 z_{t-1} \ ,$$

Here Φ_1 is AR filter coefficient, θ_1 is the MA filter coefficient, x_t and x_{t-1} is the value of the function x_t and z_t and z_{t-1} is the estimated noise at times t and $t-1$ respectively. Since value of x_t can be estimated with only x_{t-1}, this is an AR (1) process, similarly since noise at time z_t can be estimated with only its previous estimate z_{t-1}, the noise model is MA (1). The estimation of AR and MA filter coefficient is usually a ratio of covariances of the respective series – i.e. Φ_1 is a ratio of covariances of the function x_t, and θ_1 is a ratio of covariances of the noise function z_t.

From preliminary analysis of several position tracks estimated by the PNM, it was deduced that each component of the INS position information – (longitude, latitude)/(easting, northing) – can be modeled as an ARMA (1) process. The AR (1) model for INS position tracking in the WGS-84 (Long, Lat) format is –

$$Lat_t = \phi_{Lat,1} \cdot Lat_{t-1} + \eta_{E,t} \, ; Long_t = \phi_{Long,1} \cdot Long_{t-1} + \eta_{Long,t}$$

An important characteristic of a filter is stability. Stability ensures that the filter output is bounded. If the filter is unstable, the filter output may grow unchecked increasing the error. The stability of above filters is ensured by the following condition – $|\Phi_{Lat,1}| \le 1$, and $|\Phi_{Long,1}| \le 1$, presented in the figure below. The focus of the mobility model is noise modeling. The preliminary models have *not* performed complete noise model analysis. A PNM was tested at Fort Hood, was analyzed using the above model.

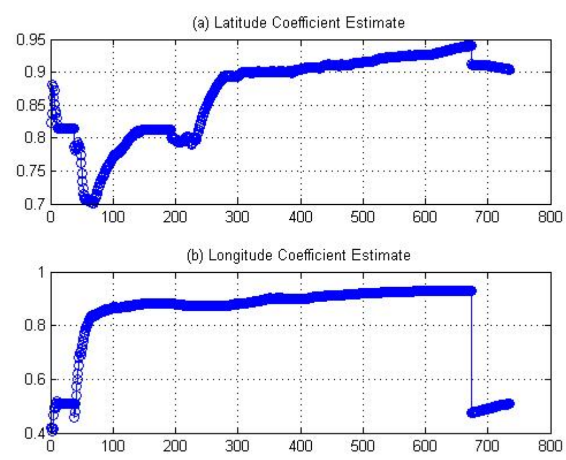

Figure 22 – Mobility Estimation Analysis – (a) Latitude filter coefficient - $\Phi_{Lat,1}$, (b) Longitude filter coefficient - $\Phi_{Long,1}$.

It can be observed from Figure 22 that filter coefficients vary between 0 and 1; proving that the applied mobility estimation filters for latitude and longitude are stable. Figure 23 (a) provides an overlay of the original track with the AR (1) estimated track. In the overlay it can be seen that the position estimates are very close to the original.

However, Figure 23 (b) it can be seen that the estimated track has overshoot, especially while turning corners. The overshoots occur due the abrupt change in heading of the track. The mobility estimation in its current state is incapable of estimating this information. However, with the principle component analysis proposed in Section 2.1.2 – INS Mechanization, the heading information can be estimated and the position estimation filter can incorporate this information, thereby reducing estimation errors.

In INS mechanization it was also stated errors in the original track occurred due to several reasons – incorrect step length model and gyro drift and compass misalignment. The heading errors introduced due error gyro drift and compass misalignment can be first modeled with the AR (*p*) technique to reduce estimation errors. The filtered sensors outputs can be then used to determine the heading. In this way, mobility modeling can be used to reduce the INS position errors. It should be noted that the AR (1) predictive model fits the INS tracks generated with the Vectronix PNM. However, since the mechanization of the INS system proposed in this report is different, the mobility estimation model for the INS may be different.

Similar use of mobility modeling is also envisioned for the TOA positioning, however due to lack of actual TOA range or position data, such analysis has not been conducted.

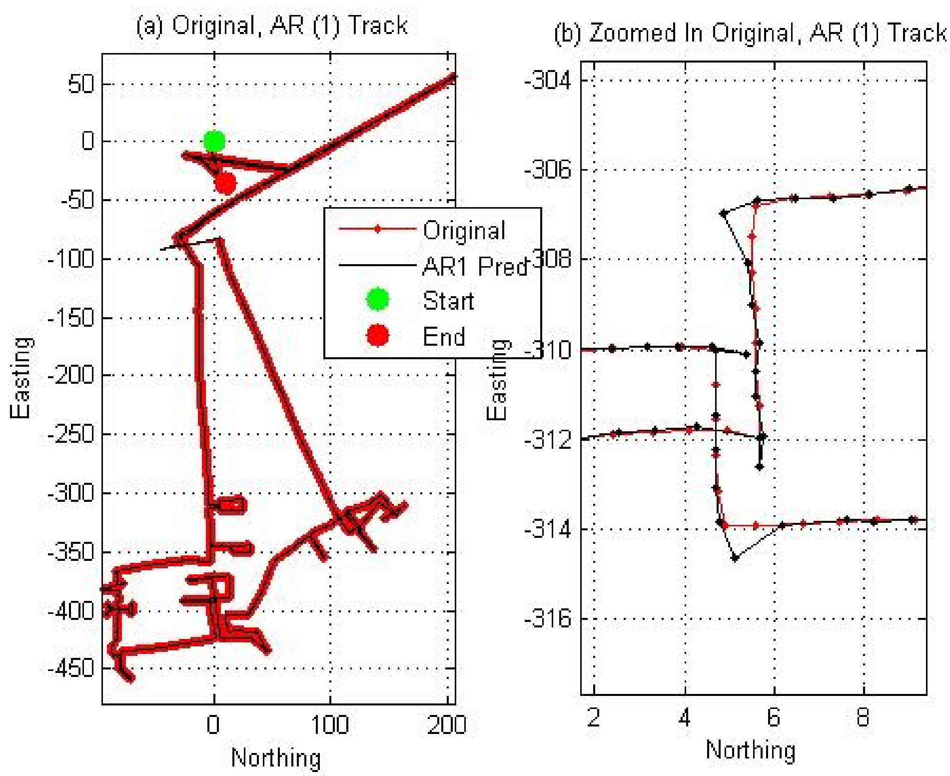

Figure 23 – (a) Original and AR (1) track – 2.7Km underground facility trajectory, (b) Zoomed In view – Original and AR (1) predicted tracks.

3.4 Product Analysis

3.4.1 INS Sensor Board / Vectronix DRC

The INS Sensor Board, shown in the figure below, is small (55mm x 70mm x 7mm) and inexpensive. In addition, the board is highly adaptable to advancements in sensor technology. As higher performance MEMS become available, old components can be replaced without significant changes in the system design. The onboard sensors include a tri-axial accelerometer, tri-axial gyro, and tri-axial magnetometer sensor suite that form a 6-degree of freedom (DOF) Inertial Measurement Unit (IMU). The IMU will measure changes in mobility and orientation and will consist of high-performance sensors in order to reduce measurement drift. The sensor board also includes a pressure sensor (barometer), for determining relative altitude, and an analog-to-digital converter that will quantize the IMU sensor information. The bias drift errors which are common to all INS sensors will be addressed via sensor fusion algorithms managed by the iTrax03 GPS receiver / INS pre-processor and SBC components of the system. Although low-level I/O drivers have been developed for the Sensor Board to communicate with the GPS receiver / INS pre-processor, the device requires further integration efforts that will exceed the ONR Phase II timeframe. For this reason, we will use the Vectronix Dead-Reckoning Computer (DRC) for the Phase II prototype.

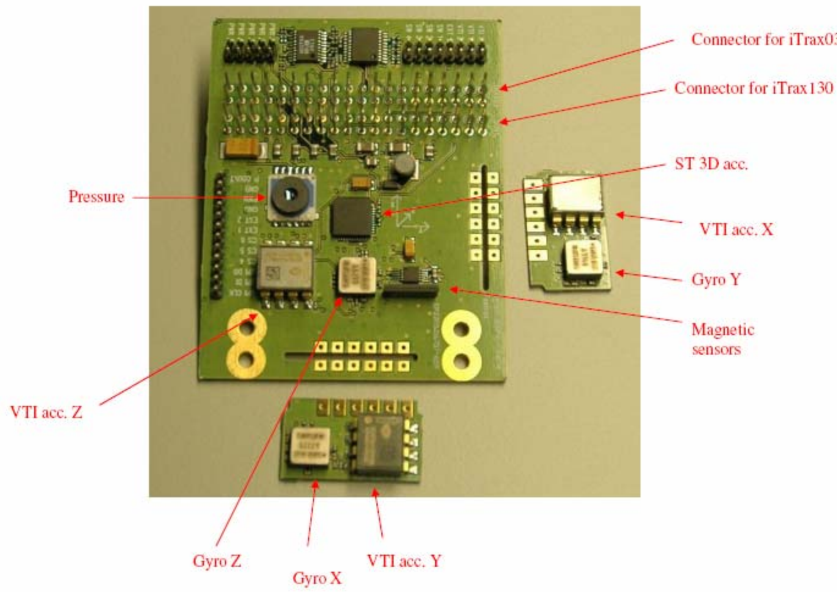

Figure 24 – INS Sensor Board.

The DRC (shown in the figure below) is small (49mm x 33mm x 13.5mm) and is currently in production and available for purchase. Several DRC units have been acquired, integrated and tested by our Mercury system engineers. From preliminary test results, the error over distance traveled during navigation in a 2-Dimensional GPS-Denied environment with arbitrary magnetic interference sources was approximately 3%-5%. Additional work is being done by Vectronix to further improve the accelerometer sensor performance of the DRC in order to more accurately detect a variety of motions beyond forward walking, including sideways and backward motions. For example, an autonomous step-scale and misalignment calibration (Helmert Calibration) has been developed. Additional Enhancements/improvements in the machine-machine interface are also underway such as a function to increase the reliability of data exchange between the DRC and host computer is under consideration. The DRC consists of a tri-axis accelerometer, a tri-axis magnetometer and a micro-controller capable of providing fused position estimates in NMEA-0183 compatible and proprietary Vectronix sentence formats. With the current sensor configuration only 2-D navigation is attainable and heading errors will accumulate

Figure 25 –Vectronix DRC.

quickly in the presence of long-term magnetic disturbances. The step-model is also a limitation of the DRC, as it is currently a static model that averages the step length of the navigating personnel. A function to detect whether the sensor is in a prone orientation is included and an accurate azimuth reading is still produced while in this mode; however, no change in position can be detected while the sensor is operating in this fashion. Significant advantages of the DRC solution are relative to its ability to be mounted practically anywhere on a user's belt or torso area as well as the fact that it is a completely self-contained INS system in a small package that already meets the SWAP requirements of the ONR project.

For the DRC to meet the full ONR system requirements, a barometer and gyroscope must be integrated. The barometer will enable 3D positioning and the gyro will augment the DRC's magnetic compass for more accurate heading determination. Utilizing the DRC, we can focus on the barometer and gyro efforts and develop the position fusion and mobility estimation algorithms discussed earlier. Due to the fact that the DRC does not currently meet the system cost goal for productization, the Sensor Board will eventually replace the DRC and the Phase II algorithms will be ported to the new device. This process will require minimal additional effort, mostly centered on tuning the position fusion algorithm to the Sensor Board characteristics.

3.4.2 ITT Clique Member Radio/WSRT

ITT, Mercury Data System's (MDS) subcontractor, will provide unique RF ranging and communications technology to support Marine Corps operations in open fields, urban areas, buildings, and in caves. One key to accurate navigation in GPS denied environments for prolonged periods of time is accurate RF ranging/TOA updates to the fused sensor and GPS solution. Depending on the scenario and expected propagation, clique members entering a building, for example as shown in the figure below, could supplement CMRs with additional CMR reference units in three dimensions to improve the probability of finding a good propagation path to the clique members in the building. In addition, the RF ranging update rate could be increased for clique members in the building providing smooth and accurate tracking during the exercise.

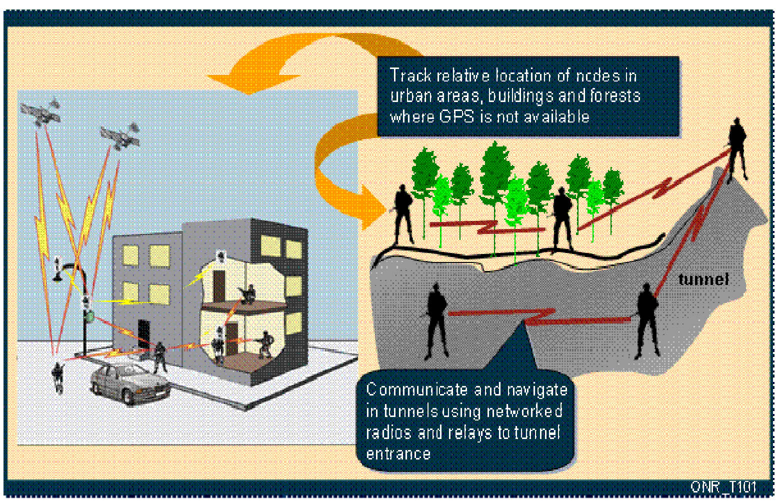

Figure 26 – RF Ranging and Networking Combine to Solve the Navigation and Communications Problems in Harsh Environments.

The TOA processes will use data available from the physical and network layers of the CMR such as signal-to-noise ratio, RAKE multipath taps, and best reference dilution of precision (DOP) combinations to perform data screening algorithms that will identify the four best ranging partners among the universe of potential ranging partners in the clique.

As illustrated in the figure below, the typical TOA ranging system (McCrady, et al., 2003, McCrady et al, 2004) comprises fixed reference CMRs and mobile CMR that can also be used as references. A mobile CMR uses up to four reference CMRs to determine its position in three dimensions via trilateration. The TOA position is fused with position estimated via INS and GPS (or other source of absolute position when available) via the PosiFusion™ process. Once the mobile CMR determines its location, it can transmit the

location coordinates to interested parties using its standard communication protocol. TOA are used to determine the range to each reference CMR and trilateration determines the location of the mobile CMR with respect to the reference CMR. The location solution can be relative to the local reference coordinate system or absolute if the references have GPS coordinates. When using absolute location, the accuracy of the reference CMR coordinates contribute to the overall system error. Multiple message exchanges are used between the mobile and reference CMR to determine the TOA. The number of multiple trials to each reference CMR can vary depending on the severity of the multipath.

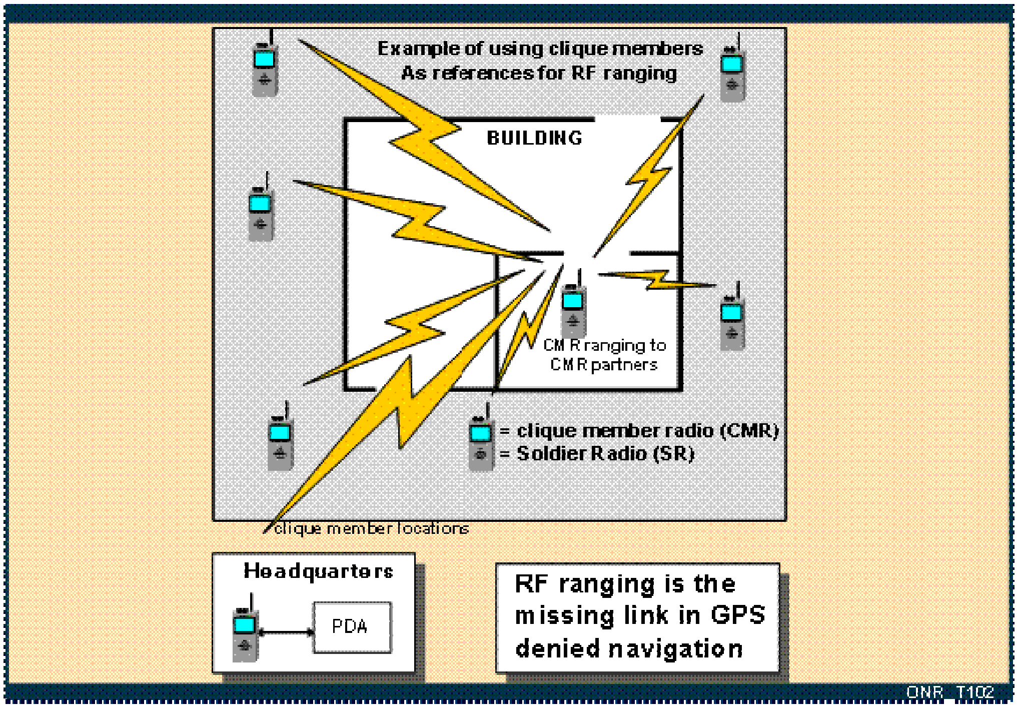

Figure 27 – Clique Members Rely on RF Ranging for Real Time Navigation Updates When GPS is denied.

3.4.2.1 CMR RF Ranging/TOA Technology Concept

The RF ranging/TOA capability was developed by ITT during the SUO SAS program mentioned above using a 32MHz bandwidth. This RF ranging approach for the NAVGPSDE Program is based on integrating the SUO SAS RF ranging technology into the Wearable Soldier Radio Transceiver (WSRT), serving as the CMR, using a -3dB bandwidth of 2.4 MHz (chip rate of 4.8Mcps). WSRT runs SRW 1.2Mcps EW Mode, implying a chip rate of 1.2Mcps and a -3dB bandwidth of .6MHz. An ITT internal R&D program ported the SRW 4.8Mcps Extended Warfare (EW) Mode to the WSRT and performed laboratory and field tests to verify performance. Key performance parameters such as sensitivity and packet completion rate versus Eb/No were performed and no shortcomings were noted compared to ITT's SLICE radios that support all SRW chip rates from .5-32Mcps. This provides a head start for our ONR BAA 06-007 Phase II demonstration because the SRW 4.8Mcps EW Mode has already been ported to the WSRT.

During Phase I, analysis of the methods to port RF Ranging/TOA to the WSRT was conducted, in addition to analysis of operational performance on the WSRT platform. During Phase II, RF ranging/TOA will be ported to the WSRT. Given the hardware improvements made in transitioning from SUO SAS (the last platform to run RF ranging/TOA) to SLICE to the WSRT, there are no expected limitations with respect to resources such as FPGA gate count and processor execution time. Processors and FPGAs have been upgraded for reduced power and improved throughput. Both FPGA gate count and processor execution time will be monitored carefully during integration. In addition, the band limiting SAW filter in the RF has been upgraded to improve group delay variation characteristics and basic TOA accuracy.

We will be integrating and demonstrating both single frequency (non-QMFR) and QMFR RF ranging capabilities in the CMR. Using QMFR and a leading edge curve fitting algorithm will provide mitigation in severe multipath. New leading edge curve fitting tables (due to chip rate reduction from 32Mcps to 4.8Mcps) are in process. The initial performance test shows that QFMR can improve our accuracy by a factor of 2 to 1.5-2.5m (CEP) under the worst case multipath conditions (McCrady et al, 2004).

3.4.3 Fastrax iTrax03 GPS Receiver / INS Fusion Pre-Processor

Mercury has researched the Fastrax iTRAX03 GPS receiver component (depicted in the figure below) and has selected this component to provide support for GPS data as well as providing INS processing/fusion capability in a single device roughly the size of a stamp (22mm x 23mm x 2.9mm). The iTRAX03 unit utilizes 40% of its processing capability toward GPS functionality which leaves 60% for the INS fusion processing. The device supports Assisted GPS; a feature that will reduce Time-to-First-Fix (TTFF) and minimize localization/calibration time of the clique.

Figure 28 – iTrax03 GPS Receiver / INS Fusion Pre-Processor.

Access to raw pseudo range measurements will enable optimization processing for enhanced GPS accuracy. Differential GPS support allows the system to compensate for localized errors due to atmospheric delays - effectively reducing GPS SEP. Another major advantage of this component is the built-in Kalman Filter library that can be leveraged for the GPS pre-processing.

Additional rationale for using this component include the presence of a high sensitivity GPS receiver; the ability to derive GPS data from Pseudolites; low power consumption; and a Software Developers Kit (SDK) which includes a Kalman Filter library; direct connectivity with INS Sensor Board and embedded processor; and the capability to tightly couple GPS, INS and Pseudolites via SDK configuration.

3.4.4 Sonic Instruments RSS Radar Velocimeter

Mercury Data Systems is currently testing the Sonic Instruments Radar Speed System (RSS) radar velocimeter prototype (shown in the figure below). The sensor measures the Doppler Effect – change in frequency and wavelength perceived by an observer moving toward the wave while it is being received – to calculate the ground speed of a person. The velocimeter consists of a DSP and I/O controller, along with supporting chipsets.

The system integration of the velocimeter data is focused on complimenting the INS accelerometer component. The output will be used to validate and compliment the INS data providing a means for the system to overcome any step length errors introduced by the INS step model by supporting all mobility modes. The velocimeter can be used to increase the accuracy of the INS and itself has an estimated accuracy of ±1% of distance traveled, based on MDS testing results.

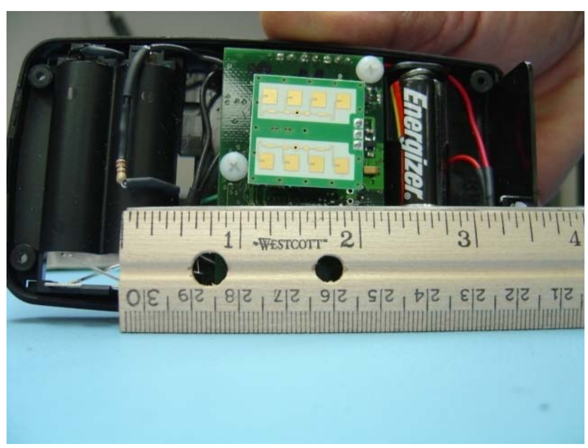

Figure 29 – Velocimeter prototype.

3.4.5 Kent ChLCD / Trident WD

Several components were evaluated for the visualization component of the ONR system. At this point the Kent Displays, Inc. Cholesteric Liquid Crystal Display (ChLCD) Module appears to be the most cost-

effective component. As a result, the device is targeted for the productization phase. Kent has experience working with DARPA to produce ChLCD technologies for military applications. The Kent devices are general-purpose monochrome or full color graphic display modules suited for battery powered portable devices and display applications. The modules include a wide viewing angle and are sunlight readable. The display is a reflective cholesteric liquid crystal display that takes full advantage of the technology’s unique “No Power” image retention attribute. The embedded display controller generates the unique ChLCD drive waveforms and provides automatic temperature compensation. The SPI-compatible interface to the embedded controller simplifies system integration using a minimal number of I/O resources and controls all display operations, from downloading image data to triggering display updates. These units can also be made readable for use at night or in limited light environs via the addition of a light source layer. Kent also produces an Infrared display which is readable at night via the use of night vision goggles as well as a flexible display system. These displays will need to be mounted in an enclosure with controls to provide the display unit for this system. MDS plans on placing these units into an enclosure similar to that used by the Trident WD unit as shown below.

The development efforts necessary to produce an enclosure and operator controls for the Kent display exceed the ONR Phase II timeframe. As a result, the Trident Wearable Display (WD) will be used for the ONR Phase II prototype. Although the WD does not meet the cost requirements for productization, it will provide a great platform to prove the visualization concepts of the ONR project. The WD is both small in size (114mm x 66mm x 25mm) and rugged (designed for MIL-STD- 810F and MIL-STD-461E compliance). Using a 2.8” QVGA (320x240) LCD with an LED backlight, the WD provides sunlight-readability and night vision goggle (NVG) friendly operation. As an added feature, specifically designed for operation in hostile environments, the display includes a recessed LCD “kill switch” for instantaneous zero light emissions.

The operator interface consists of a 4-way joystick with integral press-to-select capability and two additional function buttons. All buttons provide tactile feedback, and are fully programmable for control of any host computer application. In addition to monitoring and control functionality, the WD has a programmable vibration capability, providing operator-defined alerts with adjustable cadences for further hands-free operation. Mounting the WD is normally done on the operator’s forearm, but the straps are Modular Lightweight Load-carrying equipment (MOLLE)-compatible, allowing easy interfacing with standard military gear. Using a small-diameter USB cable, the WD draws power from and communicates with the host computer. This cable can be routed up the arm for easy connection with a back-mounted host computer.

Figure 30 – (A) Kent Infrared Display; (B) Kent Flexible Display; and (C) Trident Enclosure w/ Controls.

3.4.6 Custom SBC / Arcom Vulcan SBC

Mercury has researched various processor modules and commercial-of-the-shelf (COTS) single board computers (SBC's). The advantage of using a device similar to a SBC is that all processing and peripheral support is integrated on one small printed circuit board (PCB). Although several SBC's are available that meet the system performance goals, none have been identified that meet the desired size and cost goals for productization. As a result, Mercury will develop a custom SBC solution for productization utilizing Freescale Semiconductor's ColdFire embedded microprocessor for sensor fusion and integrated peripheral connections for visualization and HMI support. The ColdFire processor features multiple connectivity peripherals including two Ethernet, USB 2.0, I^2C, and Serial (RS-232/SPI) interfaces required for the Visualization, INS/GPS, CMR, Military Radio and power subsystems. The ColdFire core also provides a Memory Management Unit (MMU), dual precision hardware Floating Point Unit (FPU) and up to 410 (Dhrystone 2.1) MIPS at 266 MHz – all of which ensure the sensor fusion algorithm will operate as fast and accurate as possible. In addition, the device offers an encryption accelerator for secure network communications to augment the security features provided by the CMR.

The custom SBC development efforts will exceed the ONR Phase II timeframe; hence, Arcom's Vulcan SBC (shown in adjacent figure) will be implemented for the Phase II prototype. The Vulcan SBC is a low-power PC104 format (96mm x 91mm) based on Intel's 533MHz IXP425 XScale network processor. The features include dual 10/100baseTx Ethernet ports with hardware accelerated encryption (DES, 3DES, AES) and authentication (SHA-1 and MD5), four (4) serial ports, four USB 2.0, digital I/O, real time clock (RTC) with 5 day+ backup, tamper switch input, onboard and CompactFlash (CF+) expansion. The device averages 3.5W power consumption and can operate within a range of -40 degrees Celsius to +85 degrees Celsius (extended range version). The IXP425 supports software emulation of floating point arithmetic which will require performance validation to meet ONR system requirements

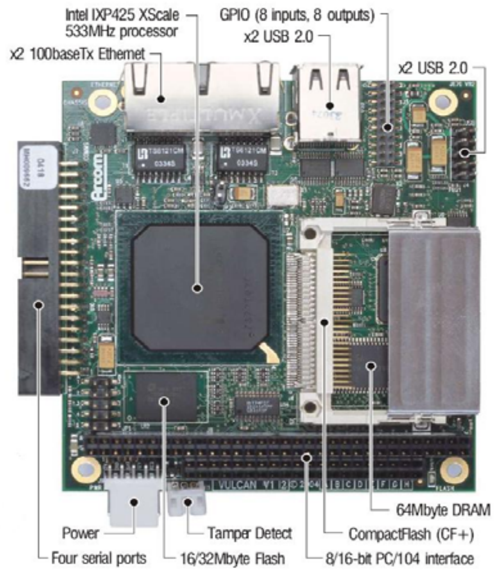

Figure 31 – Arcom Vulcan SBC.

4 Technical Accomplishments

The following lists the accomplishments and findings for each of these technical objectives addressed in this BAA.

Table 8: Technical Accomplishments and Benefits.

Objectives	Accomplishments	Proposed Solution Advantages
Objective 1: Research, design and develop a multi-sensor positioning system capable of self/remote localization by each clique member.	Reviewed USMC platoon structure, roles and operational tactics	Solution uses USMC platoon organization and tactics to reinforce position estimation (eLNS) Complementary, collaborative and redundant positioning that provides failover support Tightly coupled GPS, INS and Pseudolite integration for enhance accuracy Strapdown INS system for range free navigation Incorporation of velocimeter for enhanced velocity/distance determination Enhanced orientation determination via gyro and magnetometer integration and Principle Component Analysis integration Enhanced mobility state algorithms support sideway and backwards motions Automated recalibration of INS sensors Enhanced position estimation through integrated TOA and QMFR algorithms ITT TOA and QMFR range estimates equivalent to UWB – but greater distance and more impervious to multipath Automated coordinate system determination Automated detection of clique member positions and automated referential alignment Integrated support for location beacon updates – provide position
	Completed an Interface Control Document (ICD) with ITT for integration of TOA Ranging processes developed for the DARPA SUO SAS program	
	Researched and qualified various INS systems and INS component configurations	
	Researched and designed innovative PDR techniques for a mechanized INS system	
	Designed and developed interface software for Vectronix Dead Reckoning Computer. Characterized system performance.	
	Designed and developed interface software for Vectronix Core Navigation System. Characterized system performance.	
	Designed and developed a velocimeter prototype	
	Designed methods to implement TOA ranging algorithms on radio platform	
	Reviewed various coordinate system localization and initialization methods, including Self Positioning Algorithm, DV-HOP, HOP-TERRAIN, Refined Statistical Localization and SeRLoc	
	Designed enhanced coordinate system localization and initialization methods to support 3D localization v. 2D localization	

Objectives	Accomplishments	Proposed Solution Advantages
	Researched approaches for auxiliary data source integration • Loran • Pseudolites	error bounding Low cost, high sensitivity GPS receiver that also supports A-GPS, DGPS, Pseudolites and tight INS coupling – fast FTTF and system initialization Secure localization Error control algorithms provide fault tolerance and ability to localize via ranging with fewer than three neighbors Optional RBCI integration for cross DOD & NATO support Optional integration of optical flow and tracking for position estimation enhancement Optional integration of robust, real time 3D map building for reconnaissance Optional integration of foot borne INS for longer duration range free navigation
	Researched variety of GPS receiver systems	
	Researched optical tracking and map building papers and technologies	
	Researched optical flow papers and technologies	
	Designed and developed Mobility Estimation Models for INS and RF based localization	
	Researched and analyzed a distributed protocol based on eLNS algorithm to distribute position information in time and space	
	Researched and analyzed an iterative localization approach for position determination by mobile personnel	
	Evaluated QMFR capabilities for minimization of multipath effects during TOA ranging. Evaluated portability of QMFR to CMR	
	Evaluated the previously developed an innovative TRPS and TDS algorithms	
	Evaluated technology integration with Radio Based Combat ID Program and developed system architecture	
Objective 2: Research, design and develop fusion algorithms for the multi-sensor positioning system.	Researched and characterized multiple approaches to sensor fusion, including various tight and loose coupling techniques	More accurate position estimation through • State prediction • Next Position prediction • Sensor fusion • Prediction fusion Optional integration of additional sensors
	Developed an innovative PosiFusion™ algorithm based on Kalman Filtering	
	Designed and developed mobility estimation models that enable position estimation error detection	

Objectives	Accomplishments	Proposed Solution Advantages
Objective 3: Research, design and develop algorithms to initialize and maintain a referential coordinate system for the clique.	Identified and analyzed approaches to initialize and calibrate position estimates throughout platoon without use of GPS. Methods evaluated included the SPA, DV-Hop, Hop-TERRAIN, RSL, SeRLoc and SCPA Identified and analyzed methods to share individual position estimates throughout clique Researched and designed methods to transform referential coordinate systems to global coordinate systems Researched and designed methods to use map objects and landmarks to initialize and reinitialize referential coordinate systems	Automated initialization and calibration and propagation of relative clique member positions – without need for absolute positioning source. Automated transformation of clique member positions through manual rotation of referential coordinate system to local/global coordinate system Ability to use map landmarks and waypoints to initialize referential coordinate system
Objective 4: Research, design and develop distributed, fault tolerant voting algorithms to synchronize individual position estimates throughout the clique.	Evaluated CMR capabilities for distributed localization using TOA ranging Evaluated approaches to multilateration that provide anomaly detection Researched and designed an enhanced Leapfrog Navigation System Researched and designed an iterative localization approach that employs error control mechanisms Reviewed capabilities of CMR to eliminate spoofing, Sybil and wormhole attacks Researched and designed an approach to reinitialize clique positions via landmarks, map objects and absolute position updates	CMR two way ranging eliminates need for clock synchronization across network TDS algorithms determine best ranging partners via RF characteristics TRPS algorithms determine bets ranging partners using mobility state & DOP characteristics Iterative localization validates neighbor position estimates Waveform threat resistance Reinitialization of all clique positions when any absolute reference is available
Objective 5: Research, design and develop visualization capabilities for displaying the relative locations of clique members.	Reviewed numerous display hardware systems Researched ergonomics, SWAP and sensibility aspects for visualization Evaluated portability of	Simplified visualization of maps and personnel: • Range • Bearing • Coordinates • Landmarks • Waypoints

<table>
<tr><th>Objectives</th><th>Accomplishments</th><th>Proposed Solution Advantages</th></tr>
<tr><td rowspan="3"></td><td>TrakPoint UI solution</td><td rowspan="3">Minimal lightweight display:
• Daylight readable
• NVG compatible
Path towards flexible, wrist mounted display</td></tr>
<tr><td>Evaluated RBCI UI solution</td></tr>
<tr><td>Evaluated Augmented Reality UI solution</td></tr>
<tr><td rowspan="9">Objective 6: Research, design and develop user interface capabilities that enable simplicity and ease of use.</td><td>Reviewed USMC platoon structure, roles and operational tactics</td><td rowspan="9">Automated localization processes that incorporate and utilize USMC tactics to enhance localization accuracy
Simplified system configuration and support for mission data:
• Personnel
• Maps
• Waypoints
Automated system initialization and calibration
Simplified messaging with processes to:
• Predefine text messages
• Select text messages from drop down menu
Compromised Device controls</td></tr>
<tr><td>Researched and designed system configuration methods</td></tr>
<tr><td>Researched and designed system initialization methods</td></tr>
<tr><td>Researched and designed user control capabilities for visualization – zooming, panning, sectoring</td></tr>
<tr><td>Researched and designed automated mesh network configuration</td></tr>
<tr><td>Researched and designed simplified communications (text messaging) methods</td></tr>
<tr><td>Designed and developed ICD standard for text messaging</td></tr>
<tr><td>Researched and designed automated methods for self localization and clique position reporting</td></tr>
<tr><td>Researched and designed methods for local device zeroization and remote device zeroization.</td></tr>
<tr><td>Objective 7: Research, design and develop communications processes to support:</td><td></td><td></td></tr>
<tr><td>• Locating Beacons</td><td>Researched and designed method for using CMR systems as fixed and man-portable locating beacons</td><td>Integrated locating beacon support via multiple options:
• Local beacons
• Remote beacons
• CMR
• Loran (calibrated)
• Pseudolites
Secure transmission of beacon</td></tr>
</table>

Objectives	Accomplishments	Proposed Solution Advantages
		data via signal encryption
	Researched and designed method for using Loran systems as fixed and vehicle- portable locating beacons	Security embedded in RF waveforms: • Localization security • Communications security Threat security
	Researched and designed method for using pseudolites systems as fixed and vehicle- portable locating beacons	
	Evaluated locating beacon security requirements	
	Researched NSA Suite B certification requirements	
• Security	Evaluated secure localization threats and requirements	Simplified messaging architecture. Simplified user interface Communications security
	Evaluated mobile network security requirements	
	Evaluated CMR capabilities for supporting secure localization and network security requirements	
	Reviewed SALUTE messaging approach	
• Text Messaging	Reviewed JVMF messaging approach (limited)	CMR is a military grade radio • Support for JTRS compliant military radio interface • Multi-hopping, ad-hoc networking capability provided with no pre-existing infrastructure (references) • Anti-Jam waveform • (LPI/LPD) • COMSEC/TRANSEC (Type3 AES with path to Type1 Crypto) • Optimum building penetration • Maximum communication range provided Optional support for alternate military radios via RBCI integration Optional support for APRS radios
	Designed simplified and extendable messaging architecture	
	Designed and developed ICD standard for text messaging	
	Researched interface methods for military radio	
• Military Radio Interface	Designed software interface for	

Objectives	Accomplishments	Proposed Solution Advantages
	military radio	BAA SWAP goals can be achieved with production systems and USMC will have various options to increase system performance and usability Systems can maintain accurate location for well over 8 hours required by spec (up to 24 hours battery life for standard military batteries
	Designed hardware interface for military radio	
	Designed and developed ICD standard for military radio interface	
	Reviewed capabilities for RBCI integration, which may provide connectivity to various military radio systems including SINCGARS, ASIP, AIR SIP and Spearhead radios	
	Reviewed NPS APRS radio capabilities for secure, long range, low power, low cost transmission	
	Reviewed numerous system component alternatives	
Objective 8: Create objective system specifications that meet program Size, Weight and Power goals.	Designed system architecture	BAA cost and performance goals can be achieved with production systems and USMC will have various options to increase system performance and usability
	Defined system options	
	Defined SWAP roadmap	
	Reviewed numerous system component alternatives	
Objective 9: Research, design and develop system configuration models that meet program Performance capabilities and Cost goals	Designed system architecture	
	Defined system options	
	Defined system roadmap	

5 Proposed Future Work Effort Recommendations / Schedule

We recommend focusing our Phase II efforts on the completion of our design, acquisition and integration of HW components, development and integration of SW components, construction of the prototype system and system verification and validation through lab and field testing and demonstration.

Specifically, the tasks/activities listed in Table 9 will be completed in Phase II.

Table 9: Proposed Future Work Effort/recommendations for Phase II.

Research and Development Objective	Recommended Tasks for Phase II
Objective 1: Research, design and develop a multi-sensor positioning system capable of self/remote localization by each clique member.	▪ Development, integration, and testing of control/logic SW required to better estimate distance traveled by comparing velocity measurements with accelerometer data to aid in step detection. ▪ Development, integration, and testing of signal processing SW required for heading determination via Gyro and magnetometer ▪ Development, integration, and testing of SW algorithm required to extend 2D to 3D positioning via use of barometer. ▪ Development, integration, and testing of compensation algorithm to combine TOA and INS information based on FOM information. ▪ Development of TOA algorithms for CMR ▪ Development, integration, and testing of TOA-related SW algorithms including TRPS for selection of ranging partners (virtual anchors) and QMFR algorithm to improve ranging accuracy in multipath environments. ▪ Development, integration, and testing of eLNS-related algorithms including; o Iterative trilateration/positioning algorithm to improve localization accuracy. o Virtual Anchors selection algorithm to improve localization accuracy. o Mobility/topology control algorithm to reduce mobility impact on localization. o Error-control algorithm to bound positioning error within SEP budget. ▪ Development of ICD software, to support ranging, networking and communications ▪ Integration and Testing of system components
Objective 2: Research, design and develop fusion algorithms for the multi-sensor positioning system.	▪ Development, integration, and testing of PosiFusion algorithm based on Kalman filtering. ▪ Development, integration, and testing of mobility tracking/prediction algorithm to reduce mobility impact on localization. ▪ Development, integration, and testing of compensation algorithm to combine TOA and INS information based on FOM information.
Objective 3: Research, design and develop algorithms to initialize and maintain a referential coordinate system for the clique.	▪ Development, integration, and testing of LCS algorithm to initialize and maintain Local/Network coordinate systems for clique members/groups. ▪ Development, integration, and testing of SW algorithm required to extend 2D to 3D positioning via use of barometer.

Research and Development Objective	Recommended Tasks for Phase II
Objective 4: Research, design and develop distributed, fault tolerant voting algorithms to synchronize individual position estimates throughout the clique.	▪ Development, integration, and testing of eLNS-related algorithms including; o Iterative trilateration/positioning algorithm to improve localization accuracy. o Virtual Anchors selection algorithm to improve localization accuracy. o Mobility/topology control algorithm to reduce mobility impact on localization. o Error-control algorithm to bound positioning error within SEP budget
Objective 5: Research, design and develop visualization capabilities for displaying the relative locations of clique members.	▪ Development, integration, and testing of visualization/UI software including modifications required to automate system initialization processes to geo-locate any reference anchors/auxiliary data sources at start-up. ▪ Development, integration, and testing of SW algorithm required to extend 2D to 3D positioning.
Objective 6: Research, design and develop user interface capabilities that enable simplicity and ease of use.	▪ Development, integration, and testing of visualization/UI software including modifications required to automate system initialization processes to geo-locate any reference anchors/auxiliary data sources at start-up. ▪ Development, integration, and testing of SW algorithm required to extend 2D to 3D positioning.
Objective 7: Research, design and develop communications/networking processes to support: ▪ Auxiliary Data Sources ▪ Security ▪ Text Messaging ▪ Military Radio Interface	▪ Development, integration, and testing of zeroize functions. ▪ Integration, and testing of network and communications security functions ▪ Development, integration and testing of API required for text messaging. ▪ Development, integration, and testing of military radio interface functions.
Objective 8: Create objective system specifications that meet program Size, Weight and Power goals.	▪ Final selection, acquisition and integration of INS device and sensors based on our product analyses described above and availability and pricing of individual components from vendors. ▪ Acquisition, integration, and testing of selected system components including: o SBC board, sensors board, and CMR radio. o Geo-location core (INS) and sensors. o GPS receiver. o Display unit. ▪ Design and development, and testing of system board including layout, place and route and precision timing ▪ Design and development, and testing of CMR ASIC including board integration. ▪ Design, development, and evaluation of system encasing/packaging including ruggedization.

Research and Development Objective	Recommended Tasks for Phase II
Objective 9: Research, design and develop system configuration models that meet program Performance capabilities and Cost goals.	▪ Final selection, acquisition and integration of INS device and sensors based to meet cost goals. ▪ CMR ASIC design ▪ Develop performance vs. cost matrix to help select system components and identify future enhancements.

Table 10: Proposed Schedule for Future work effort/schedule for Phase 2.

ID		WBS	Task Name	Duration	Start	Finish
1		**1**	**ONR BAA_06_007 Phase 2**	**170 days**	**Tue 5/1/07**	**Mon 12/24/07**
2		**1.1**	**Task 1 - Detailed Design**	**165 days**	**Tue 5/1/07**	**Mon 12/17/07**
3		**1.1.1**	**System Design**	**165 days**	**Tue 5/1/07**	**Mon 12/17/07**
4		1.1.1.1	System Design review Based on ONR Feedback	7 days	Tue 5/1/07	Wed 5/9/07
5		1.1.1.2	Develop Low Level Design Specifications	14 days	Tue 5/1/07	Fri 5/18/07
6		1.1.1.3	Develop System Design Document	165 days	Tue 5/1/07	Mon 12/17/07
7		**1.1.1.4**	**HW System Design**	**14 days**	**Tue 5/1/07**	**Fri 5/18/07**
8		1.1.1.4.1	Complete SBC Design	14 days	Tue 5/1/07	Fri 5/18/07
9		1.1.1.4.2	Complete INS MEMS sensors Design	14 days	Tue 5/1/07	Fri 5/18/07
10		1.1.1.4.3	Complete GPS Reciever Design	14 days	Tue 5/1/07	Fri 5/18/07
11		1.1.1.4.4	Complete CMR Radio Design	14 days	Tue 5/1/07	Fri 5/18/07
12		1.1.1.4.5	Complete Display Unit Design	14 days	Tue 5/1/07	Fri 5/18/07
13		1.1.1.4.6	Complete HW Interfaces	14 days	Tue 5/1/07	Fri 5/18/07
14		1.1.1.4.7	Complete Enclosure/Casing Design	14 days	Tue 5/1/07	Fri 5/18/07
15		**1.1.1.5**	**SW System Design**	**14 days**	**Tue 5/1/07**	**Fri 5/18/07**
16		1.1.1.5.1	Complete PosiFusion Algorithm Design	14 days	Tue 5/1/07	Fri 5/18/07
17		1.1.1.5.2	Complete TRPS Algorithms Design	14 days	Tue 5/1/07	Fri 5/18/07
18		1.1.1.5.3	Complete LCS algorithm Design	14 days	Tue 5/1/07	Fri 5/18/07
19		1.1.1.5.4	Complete eLNS Algorithm Design	14 days	Tue 5/1/07	Fri 5/18/07
20		1.1.1.5.5	Complete UI SW Design	14 days	Tue 5/1/07	Fri 5/18/07
21		1.1.1.5.6	Complete SW Interfaces	14 days	Tue 5/1/07	Fri 5/18/07
22		**1.1.2**	**System Development**	**28 days**	**Tue 5/1/07**	**Thu 6/7/07**
23		**1.1.2.1**	**HW Development/Acquistion**	**28 days**	**Tue 5/1/07**	**Thu 6/7/07**
24		1.1.2.1.1	Acquire SBC	28 days	Tue 5/1/07	Thu 6/7/07
25		1.1.2.1.2	Acquire INS MEMS sensors	28 days	Tue 5/1/07	Thu 6/7/07
26		1.1.2.1.3	Acquire GPS Reciever	28 days	Tue 5/1/07	Thu 6/7/07
27		1.1.2.1.4	Acquire CMR radio	28 days	Tue 5/1/07	Thu 6/7/07
28		1.1.2.1.5	Acquire Display unit	28 days	Tue 5/1/07	Thu 6/7/07
29		1.1.2.1.6	Acquire Materials	28 days	Tue 5/1/07	Thu 6/7/07
30		**1.1.2.2**	**SW Development**	**28 days**	**Tue 5/1/07**	**Thu 6/7/07**
31		1.1.2.2.1	PosiFusion Algorithm Development	28 days	Tue 5/1/07	Thu 6/7/07
32		1.1.2.2.2	TOA/QMFR/TRPS Algorithms Development	28 days	Tue 5/1/07	Thu 6/7/07
33		1.1.2.2.3	LCS algorithm Development	28 days	Tue 5/1/07	Thu 6/7/07
34		1.1.2.2.4	eLNS Algorithm Development	28 days	Tue 5/1/07	Thu 6/7/07
35		1.1.2.2.5	UI SW Development	28 days	Tue 5/1/07	Thu 6/7/07
36		1.1.2.2.6	SW Interfaces Developemnet	28 days	Tue 5/1/07	Thu 6/7/07
37		**1.1.3**	**System Integration**	**56 days**	**Mon 6/4/07**	**Mon 8/20/07**
38		**1.1.3.1**	**HW System Integration**	**56 days**	**Mon 6/4/07**	**Mon 8/20/07**
39		1.1.3.1.1	Complete SBC Design	56 days	Mon 6/4/07	Mon 8/20/07
40		1.1.3.1.2	Complete INS MEMS sensors Integration	56 days	Mon 6/4/07	Mon 8/20/07
41		1.1.3.1.3	Complete GPS Reciever Integration	56 days	Mon 6/4/07	Mon 8/20/07
42		1.1.3.1.4	Complete CMR Radio Integration	56 days	Mon 6/4/07	Mon 8/20/07
43		1.1.3.1.5	Complete Display Unit Integration	56 days	Mon 6/4/07	Mon 8/20/07
44		**1.1.3.2**	**SW System Integration**	**56 days**	**Mon 6/4/07**	**Mon 8/20/07**
45		1.1.3.2.1	PosiFusion Algorithm Integration	56 days	Mon 6/4/07	Mon 8/20/07
46		1.1.3.2.2	TOA/QMFR/TRPS Algorithms Integration	56 days	Mon 6/4/07	Mon 8/20/07
47		1.1.3.2.3	LCS algorithm Integration	56 days	Mon 6/4/07	Mon 8/20/07
48		1.1.3.2.4	eLNS Algorithm Integration	56 days	Mon 6/4/07	Mon 8/20/07
49		1.1.3.2.5	UI SW Integratiojn	56 days	Mon 6/4/07	Mon 8/20/07
50		1.1.3.2.6	SW Interfaces Integration	56 days	Mon 6/4/07	Mon 8/20/07
51		1.1.3.3	System Integration	56 days	Mon 6/4/07	Mon 8/20/07
52		**1.2**	**Task / Milestone 2 – Construct and Demo (Lab)**	**166 days**	**Tue 5/1/07**	**Tue 12/18/07**
53		1.2.1	Complete Code Construction / Integration	14 days	Mon 8/20/07	Thu 9/6/07
54		1.2.2	Build Bread Board Prototype for Testing / Evaluation (	14 days	Tue 5/1/07	Fri 5/18/07
55		**1.2.3**	**Testing**	**62 days**	**Mon 9/24/07**	**Tue 12/18/07**
56		**1.2.3.1**	**Component Level**	**56 days**	**Mon 9/24/07**	**Mon 12/10/07**
57		1.2.3.1.1	SW Components Testing	56 days	Mon 9/24/07	Mon 12/10/07
58		1.2.3.1.2	HW Components Testing	56 days	Mon 9/24/07	Mon 12/10/07
59		1.2.3.2	System Level Testing	56 days	Mon 9/24/07	Mon 12/10/07
60		1.2.3.3	Test Summary Report	7 days	Mon 12/10/07	Tue 12/18/07
61		1.2.3.4	Lab Prototype Complete	1 day	Tue 12/18/07	Tue 12/18/07
62		**1.2.4**	**Lab Evaluation**	**1 day**	**Mon 12/17/07**	**Mon 12/17/07**
63		1.2.4.1	Lab Prototype Evaluation	1 day	Mon 12/17/07	Mon 12/17/07
64		1.2.4.2	Task 2 - Construct and Demo (Lab) Complete	0 days	Mon 12/17/07	Mon 12/17/07
65		**1.3**	**Task / Milestone 3 – Field Testing**	**170 days**	**Tue 5/1/07**	**Mon 12/24/07**
66		1.3.1	Build 5 Field Prototypes for Testing	160 days	Tue 5/15/07	Mon 12/24/07
67		**1.3.2**	**Testing**	**170 days**	**Tue 5/1/07**	**Mon 12/24/07**
68		1.3.2.1	Develop Test Plans	14 days	Tue 5/1/07	Fri 5/18/07
69		1.3.2.2	Test Design	14 days	Mon 5/21/07	Thu 6/7/07
70		1.3.2.3	Develop Test Cases	28 days	Thu 6/7/07	Mon 7/16/07
71		1.3.2.4	Execute Field Testing	6 days	Mon 12/17/07	Mon 12/24/07
72		1.3.2.5	Field Test 1 - Travel	0 days	Mon 12/17/07	Mon 12/17/07
73		1.3.2.6	Field Test 2 - Travel	0 days	Mon 12/17/07	Mon 12/17/07
74		1.3.2.7	Compare / Verify Results against Lab Tests	2 days	Mon 12/17/07	Tue 12/18/07
75		1.3.2.8	Update Test Summary Report	3 days	Mon 12/17/07	Wed 12/19/07
76		1.3.2.9	Field Prototype Complete	0 days	Mon 12/17/07	Mon 12/17/07
77		**1.3.3**	**System Verification and Validation**	**5 days**	**Mon 12/17/07**	**Fri 12/21/07**
78		1.3.3.1	System Verification	5 days	Mon 12/17/07	Fri 12/21/07
79		1.3.3.2	System Validation	5 days	Mon 12/17/07	Fri 12/21/07
80		**1.4**	**Final Technical Report**	**5 days**	**Mon 12/17/07**	**Fri 12/21/07**
81		1.4.1	Compile Test, Exercise, and Evaluation Results	5 days	Mon 12/17/07	Fri 12/21/07
82		1.4.2	Compile Vendor Materials	5 days	Mon 12/17/07	Fri 12/21/07
83		1.4.3	Compile Analysis Results	5 days	Mon 12/17/07	Fri 12/21/07
84		1.4.4	Other Material referenced/used in final report prepara	5 days	Mon 12/17/07	Fri 12/21/07
85		1.4.5	Prepare Technical Presentations	5 days	Mon 12/17/07	Fri 12/21/07
86		1.4.6	Final Technical Report Complete	5 days	Mon 12/17/07	Fri 12/21/07

Appendix

5.1 References

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5.2 Acronyms

This section includes a bulleted list of all applicable definitions, acronyms and abbreviations utilized within the document.

- 3DES – Triple Data Encryption Standard
- AES – Advanced Encryption Standard
- AHLOS – Ad-Hoc Localization System
- AO – Area of Operation
- API – Application Programming Interface
- APRS – Automatic Position Reporting System
- AP – Absolute Position
- AR – Auto-Regressive
- ARMA – Auto-Regressive Moving Average
- ASIC – Application Specific Integrated Circuit
- BAA – Broad Agency Announcement
- BER – Bit Error Rate
- C2 – Command and Control
- CMR – Clique Member Radio
- COMSEC – Communication Security
- COTS – Commercial-Off-The-Shelf
- CSMA/CA – Carrier Sense Multiple Access / Collision Avoidance
- DARPA – Defense Advanced Research Projects Agency
- DES – Data Encryption Standard
- DOF – Degree of Freedom
- DOP – Dilution of Precision. DOP is an indication of the effect of satellite geometry on the accuracy of the fix.
- DRC – Dead-Reckoning Computer
- DSP – Digital Signal Processing
- DSSS – Direct Sequence Spread Spectrum
- eLNS – extended Leapfrog Navigation System
- EW – Extended Warfare
- FBCB2 – Force Battle Command Brigade and Below
- FOM – Figure of Merit
- FPU – Floating-Point Unit
- GDOP – Geometric Dilution of Precision
- GPS – Global Positioning System
- GUI – Graphical User Interface
- HDOP – Horizontal Dilution of Precision
- HMI – Human-Machine Interface
- HUD – Heads Up Display
- HW – Hardware
- I^2C – Inter-Integrated Circuit
- ICD – Interface Control Document
- IH – Island Head
- ILS – Iterative Localization System
- IMU – Inertial Measurement Unit
- I/O – Input / Output
- INS – Inertial Navigation System
- JTRS – Joint Tactical Radio System
- JVMF – Joint Variable Message Format
- LCD – Liquid Crystal Display
- LCS – Local Coordinate System
- LED – Light-Emitting Diode
- LMs – Landmarks

- LOS – Line of Sight
- LPI – Low Probability of Interference
- LPD – Low Probability of Detection
- LSA – Link State Advertisement
- MAC – Media Access Control
- MAL – Mobile-Assisted Localization
- MCL – Monte Carlo Localization
- MD5 – Message-Digest Algorithm 5
- MDS – Mercury Data Systems
- MEMS – Micro-Electro-Mechanical Sensor
- MMU – Memory Management Unit
- MOLLE - Modular Lightweight Load-carrying Equipment
- NAVGPSDE – Navigation in GPS-Denied Environment
- NCS – Network Coordinate System
- NMEA-0183 – National Marine Electronics Association 0183 Interface Standard. Defines electrical signal requirements, data transmission protocol and time, and specific sentence formats for a 4800-baud serial data bus.
- NSA – National Security Agency
- NVG – Night Vision Goggle
- ONR – Office of Naval Research
- PCB – Printed Circuit Board
- PDOP – Position Dilution of Precision
- PDR – Pedestrian Dead-Reckoning
- PL - Pseudolite
- PNM – Pedestrian Navigation Module
- PPP – Point-to-Point Protocol
- PPS – Precise Positioning Service
- PROP – Packet Radio Organization Packets
- QMFR – Quadrature Multiple Frequency Ranging
- RBCI – Radio-Based Combat Identification
- RF – Radio Frequency
- RP – Relative Position
- RSS – Received Signal Strength
- RTC – Real-Time Clock
- SAASM – Selective Availability Anti-Spoofing Module
- SAD – Strongest Arrival Delay
- SBC – Single Board Computer
- SDK – Software Development Kit
- SEP – Spherical Error Probability
- SeRLoc – Secure Range-Independent Localization
- SINCGARS – Single Channel Ground and Airborne Radio System
- SHA1 – US Secure Hash Algorithm 1
- SPA – Self-Positioning Algorithm
- SPI – Serial Peripheral Interface
- SRW – Soldier Radio Waveform
- SUO SAS – Small Unit Operations Situational Awareness System
- SVT – State Vector Table
- SW – Software
- SWAP – Size Weight And Power
- TDS – TOA-based Data Screening
- TOA – Time-of-Arrival Radio Frequency Ranging
- TOC – Tactical Operations Center
- TRANSEC – Transmission Security
- TRPS – TOA-based Ranging Partner Selection

- TTFF – Time-to-First-Fix
- TTL – Time-to-Live
- UI – User Interface
- USB – Universal Serial Bus
- UWB – Ultra-Wide Band
- VDOP – Vertical Dilution of Precision
- VGA – Video Graphics Array. A standard for graphics displays, implying a resolution of 640x480 pixels, defined by IBM.
- WD – (Trident) Wearable Display
- WSRT – Wearable Soldier Radio Transceiver – same as CMR
- ZUPT – Zero Update